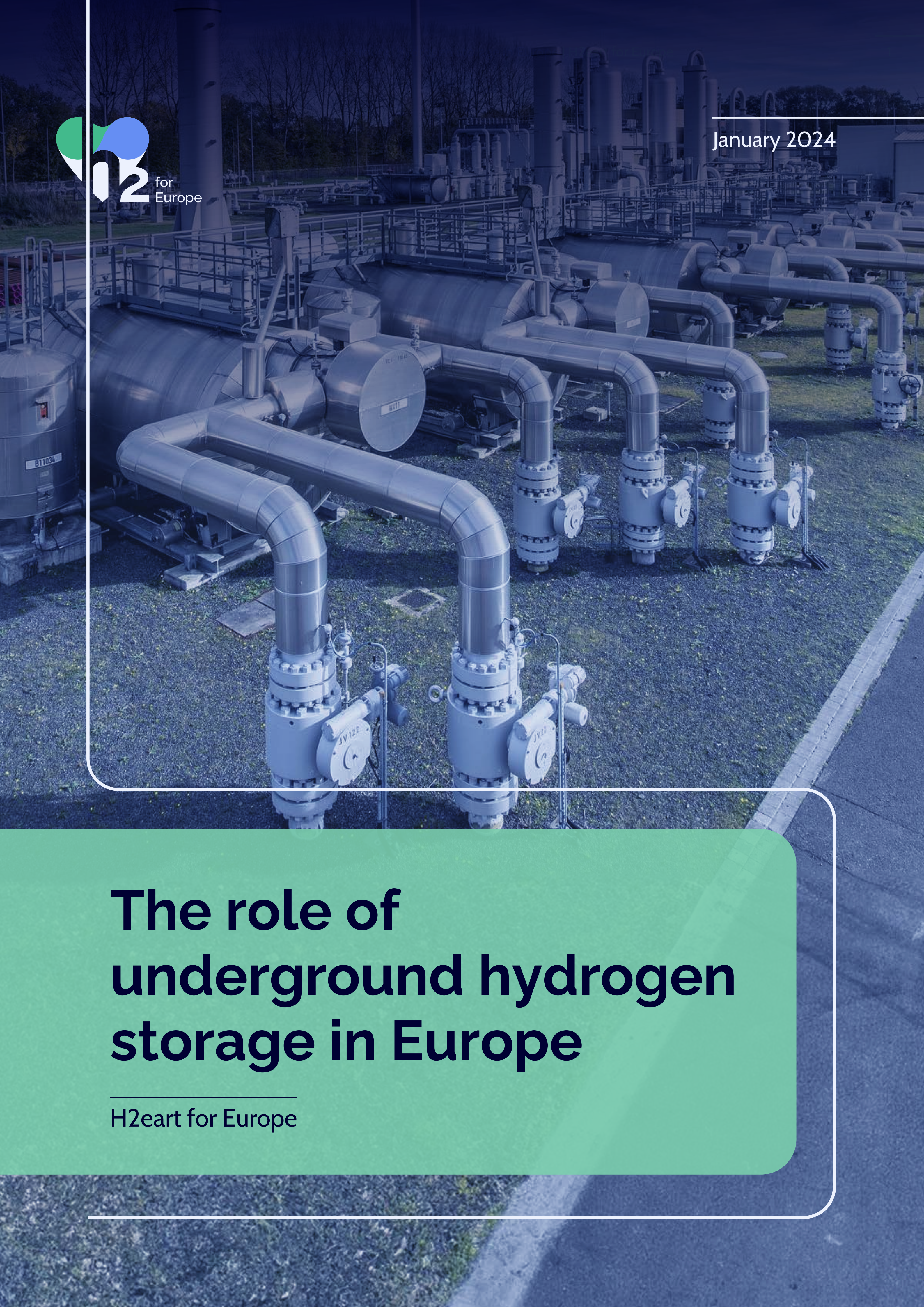

January 2024

The role of underground hydrogen storage in Europe

H2eart for Europe

Imprint

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Preface

About underground hydrogen storage

Gradually decarbonising their energy consumption due to the unprecedented challenge of climate change, most European countries are augmenting their production & consumption of renewable energy sources.

This increase in reliance on intermittently and unreliably produced energy reveals the urgent need for the development of sustainable energy storage solutions, capable of balancing out the inherent volatility in electricity production from renewable sources.

Underground Hydrogen Storage (UHS) is a low-cost and market-ready storage solution that is safe and can build on existing infrastructure resources, as well as complement a nascent hydrogen ecosystem in Europe. Currently, salt caverns, depleted gas fields, aquifers, and rock caverns are the predominately used storage technologies. Amongst these storage types, distinctions in size, withdrawal and injection rates, cycle capacity, and repurposing maturity are evident. A series of innovative UHS projects are currently being carried out within the EU to investigate and analyse repurposing potential, as well as necessary changes in plant design and layout to meet exacting standards.

About H2eart for Europe

H2eart for Europe is an EU-wide, CEO-led alliance committed to accelerating the decarbonisation of the European energy system at the lowest cost to society by scaling up the deployment of underground hydrogen storage (UHS). Launched in Brussels on 23rd of January 2024, the alliance aims to provide fact-based reports and analysis that can serve policymakers as guidance, and that utilise and build on the experience of our members, leading companies paving the future of hydrogen storage across Europe. We are committed to invest in scaling up UHS infrastructure to meet the flexibility demand in a decarbonised energy system.

This first report focusses on discussing the impactful role of UHS for the decarbonisation of the wider European energy system, including the electricity system and the hydrogen ecosystem. In the future, H2eart for Europe will develop further insights, e.g. on hydrogen storage potential and their impact on the EU energy transition. The alliance desires to proactively engage with other stakeholders on how to accelerate the energy transition and meet EU climate targets.

The organisations listed below are the founding members of H2eart for Europe. The report was prepared by the alliance in collaboration with Guidehouse as knowledge partner.

The founding partners

gasunie crossing borders in energy

HGS Powered by MVM

nafta

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About Guidehouse

Guidehouse is a leading global provider of consulting services to the public sector and commercial markets, with broad capabilities in management, technology and risk consulting. Over 1,700 of Guidehouse's 16,500 consultants are specialised in accompanying industrials, utility, investor and government clients through the energy transition.

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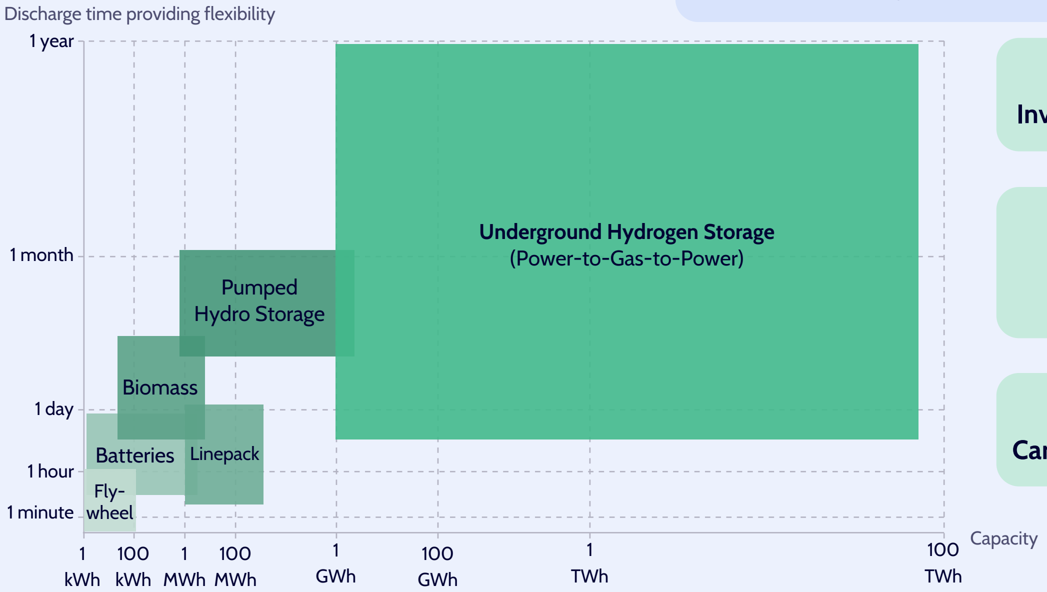
Glossary

DSO	Distribution System Operator
EC	European Commission
EU	European Union
FID	Final Investment Decision
GHG	Greenhouse gas
LCOH	Levelised Cost of Hydrogen
LCOS	Levelised Cost of Storage
PCI	Project of Common Interest
PtG	Power-to-Gas
PtGtP	Power-to-Gas-to-Power
RED	Renewable Energy Directive
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuels
SoS	Security of Supply
SSO	Storage System Operator
TSO	Transmission System Operator
UGS	Underground Gas Storage
UHS	Underground Hydrogen Storage

The role of underground hydrogen storage in Europe

Intermittently produced renewables make up an increasing share of Europe's energy supply. A solution capable of providing long- and short-term flexibility is urgently needed.

UHS is the sole social-economic solution which can solve the flexibility crisis we are facing...



Attention: Intervals on the capacity axis are exponential i.e. UHS can have almost 1 million times the capacity of a battery.

...whilst simultaneously bringing **benefits** for all players along the renewable energy chain. The below benefits are based on the comparison of two scenarios, one with and one without UHS:

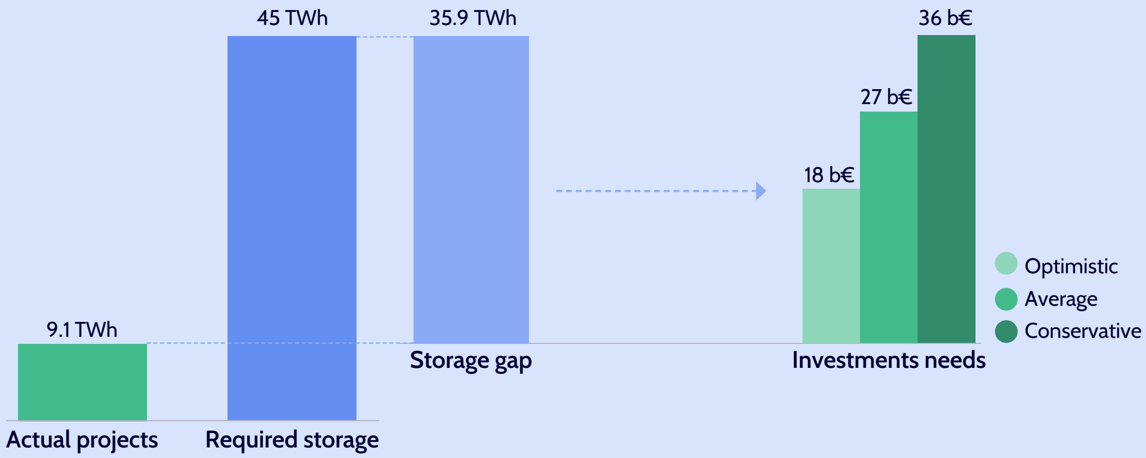
4-36%
Investment cost reduction

25%
Levelised Cost of Hydrogen reduction

70%
Carbon footprint reduction

Currently, the gap between predicted flexibility needs and actualised project pipeline is **36 TWh for 2030.**

Closing this gap would require between **€18 and €36 billion in investments.**



Policy overview

European renewable energy and hydrogen targets can only be met with the necessary supporting infrastructure. **Policy makers must take action now** to ensure a smooth roll-out of RES and the achievement of critical decarbonisation targets.

These measures might take the form of a dedicated **European Underground Hydrogen Storage Strategy**, and include:

- A defined regulatory framework which includes provision on hydrogen storage tariffication.
- Concrete hydrogen storage targets and detailed provisions for their achievement.
- Fact-based network planning which considers new facilities as well as the repurposing potential of existing infrastructure.
- Shortened permitting processes.

Executive Summary

Key findings

Faced with the more and more urgent challenge of climate change, most EU member states progressively increase the share of intermittently produced renewable energy sources (RES) in their energy mix. To ensure a stable energy supply, **RES must be coupled with clean energy storage options capable of providing the necessary flexibility**.

Underground Hydrogen Storage (UHS) is a scalable solution that unlocks hydrogen as a flexibility vector. Depending on the UHS technology and cycling rate, varying timescales for short- to long-term storage are possible. To access hydrogen's full potential, ambitious hydrogen storage projects are of the essence.

Storage Operators in Europe have already initiated 9.1 TWh of pure-hydrogen UHS projects by 2030, and plan to reach 22.1 TWh capacity by 2040. This project pipeline reflects the strong commitment to UHS technology by the energy sector. However, there is a strong necessity for project acceleration considering the predicted need of 45 TWh of hydrogen storage by 2030.

Narrowing this 36 TWh storage gap and satisfying projected hydrogen demand would require between 18 and 36 billion euros in investment. Policy makers must take action now to ensure a smooth roll-out of RES and the achievement of critical decarbonisation targets.

Targeted policy measures may take the shape of a dedicated EU Hydrogen Storage Strategy, granting hydrogen storage the attention needed for a successful and efficient scale-up. Measures must include shortened permitting processes, concrete hydrogen storage targets and provisions for detailed, fact-based network planning, taking into account the potential of repurposing infrastructure and newly built storage sites.

The European Union (EU) aims to fully decarbonise its economy by 2050, requiring a complete transformation of the energy system and its infrastructure.

The Green Deal, presented by the European Commission (EC) in December 2019, aims to achieve a minimum 55% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels, as set out in the Fit for 55 Package. The EU strategy on hydrogen, adopted in 2020, put forward a vision for the creation of a European hydrogen ecosystem aligned with the European Green Deal. As a response to the Russian invasion of Ukraine in 2022, the EC also published the REPowerEU plan to reduce the dependency on Russian fossil fuels whilst also assuring a sustainable, affordable and secure energy transition. This plan includes ambitious hydrogen targets – 10 Mton (336 TWh) of domestic production and 10 MTon of imports – for 2030.

Achieving 2030 intermediary targets as well as creating a fully decarbonised European energy system by 2050 is an ambitious task and will require an integrated and sector-coupled approach implicating both the electricity and the hydrogen ecosystem. In this integrated system, hydrogen can function as a flexibility vector, allowing the storage of large amounts of renewable energy over extended periods of time, and also connecting production locations to more distant demand centres. In this context, underground hydrogen storage (UHS) can support European energy system decarbonisation and facilitate the development of a clean hydrogen ecosystem, enabling a fully integrated system. Various reports already highlight the need for up to 100 TWh of UHS capacity as early as 2030.

UHS is key to reach the EU's ambitious targets on clean hydrogen use across various sectors, and to enable a deep decarbonisation of the electricity system. Hydrogen storage ensures a stable hydrogen supply, allows for a decoupling of hydrogen supply and demand, and facilitates the integration of hydrogen imports. In the context of electricity systems, hydrogen storage facilitates the integration of renewable energy sources (RES) and provides both the short- and long-term flexibility needed to balance out intermittently produced renewable energy. UHS unlocks the use of hydrogen as a renewable back-up fuel which can balance out variable RES production.

Investing in UHS ensures a better use of renewable energy sources from a network integration standpoint. This, in turn, allows a reduction of grid withdrawals, and decreases investment costs for the total system overall. Additionally unlocked renewables contribute to a larger supply of renewable hydrogen in the system and a lower curtailment of renewables, consequently achieving a lower levelised cost of hydrogen (LCOH) for (industrial) users. Furthermore, the increasing availability of zero carbon energy sources allows for a reduction of CO2 emissions across the electricity and hydrogen value chain.

The development of UHS across Europe depends on the geographical conditions and availability of storage sites as well as (local) storage needs. However, all storage types – ranging from salt caverns, depleted gas fields, aquifers to rock caverns – can fulfil different specifications, and will be necessary for the decarbonisation of future energy systems. The technology is scalable and has many favourable use cases indicating that its rapid scale-up across Europe is recommended. Since the development of a UHS project can take up to 10 years – depending on site characteristics and the possible repurposing of natural gas assets – the early start of projects' development is important.

As a soon to be published study by GIE indicates, the need for hydrogen storage will increase rapidly in the next years. Currently planned hydrogen storage projects are largely insufficient to cover predicted demand. By 2030, there will be a need for around 45 TWh of hydrogen storage, which is expected to grow significantly towards 2050. As of today, the project pipeline for pure-hydrogen UHS projects is 9.1 TWh in 2030, and 22.1 TWh in 2040. This indicates a significant storage gap of 36 TWh in 2030, which will grow towards 2040 based on current project outlook. In financial terms, this corresponds to an additional investment need of €18-36 billion by 2030 and a much higher investment need after.

The implementation speed of UHS largely depends on the legislative environment on both a national and European level. A dedicated EU Hydrogen Storage Strategy would create the clear regulatory framework essential for the development of UHS capacities. It should include provisions for stable investment conditions and remuneration models, incentives to develop assets and de-risking measures. The strategy should enable the swift development of hydrogen storage business and market models, where different values of hydrogen storage assets are recognised and properly monetised to create a viable business case.

While different studies report various storage needs for 2030 and beyond, the trajectory for UHS projects still shows a significant project development gap. While there are targets for the deployment of RES and the utilisation of quotas for hydrogen demand in various industries, the role of large-scale hydrogen storage is not yet clearly acknowledged. H2eart for Europe sees an urgent need to set reasonable & actionable hydrogen storage targets. Setting targets will emphasise the role of UHS as a key decarbonisation technology and prove the commitment from European policymakers to meet decarbonisation targets.

The long development times of UHS increase the risk that future storage requirements will not be met, resulting in lower decarbonisation across the energy system. As permitting procedures might take up a significant part of the development timeline, it needs to be ensured that barriers are as low as possible to develop storage assets. Simplified administrative processes are required, such as one-stop-shops and a maximum duration of certain permitting steps. Capacity building for UHS permitting procedures is required to speed up the deployment. Shorter development timelines will also result in lower cost and commercial risks associated with UHS deployment, a vital signal for operators to take serious investment decisions and develop assets.

To qualitatively and quantitatively assess the benefits of UHS integration within the energy system, there is a strong need for cross-sectoral modelling and energy system planning. ENTSO-E is currently planning to have an interlinked model with electricity, gas and hydrogen available by 2028. This interlinked model with an adequate temporal resolution is however needed as soon as possible to allow a proper assessment of the asset benefits and future energy system plans.

A combination of these measures would result in a highly effective EU Hydrogen Storage Strategy, and ultimately allow for the energy transition to be achieved in a resource-efficient and effective manner, as well as ensure decarbonisation is attained at the lowest cost for society. Consequently, urgent action is necessary from national and European policy makers.

01
Introduction and overview of European policy-making

Understanding the hydrogen context

Recent years have been marked by a strong shift in the global energy landscape away from carbon-intensive energy fuels, and towards renewable energy sources (RES). Hydrogen has garnered much attention and emerged as a technologically mature and highly applicable alternative to high-emission fossil fuels.

Globally, hydrogen consumption has increased consistently for the past decades – a trend only expected to continue as it is primarily industry-driven.[1] Use cases are continually evolving to include decarbonisation opportunities particularly targeted to hard-to-abate sectors, and specifically developed for decarbonisation purposes.

As hydrogen demand and supply develops, storage needs equally increase. Underground geological facilities are the only technologically viable infrastructure option for the storage of hydrogen, and consequently for the satisfaction of rising hydrogen demand. Underground hydrogen storage (UHS) can also play an important role in providing a long-term storage solution for energy networks which increasingly integrate a larger share of intermittently produced RES. As a result, UHS is a key element of the nascent hydrogen ecosystem, both globally and within Europe.

This report aims to highlight the importance of UHS to meet the European climate goals. Unlocking UHS deployment requires significant action related to the regulatory framework, investment uncertainty, and project development across Europe. The valuable role that hydrogen storage can play is emphasised in chapter 0, and in chapter 3, more detail is provided on the development of UHS assets. In chapter 4, the trajectory of storage developments towards 2030 and beyond is described. Also, the link between actual projects and required storage developments is further elaborated. In chapter 5, the role of UHS and its trajectory is concluded and linked to a tangible and actionable policy overview.

How EU climate & energy security legislation influences UHS deployment

Faced with the increasingly urgent challenge of climate change, the EU set out to make Europe the first climate-neutral continent by 2050. Translating this ambition into a series of legislative proposals, the EU presented the European Green Deal in December 2019. The European Green Deal introduces a series of interim goals and milestones, amongst which a 55% reduction of GHG emissions compared to 1990 levels.

The European Green Deal further influenced the Fit-for-55 Package, a legislative package which breaks down climate ambitions into actionable and concrete EU law-making. The Fit-for-55 Package simultaneously focuses on expanding renewable energy sources (RES), electrification, ensuring security of supply (SoS) and reducing dependency on fossil fuels.

The package also includes a series of more strategic legislative proposals, e.g. the EU Strategy for System Integration which illuminates the context for an integrated energy system for a climate-neutral Europe.[2]

Complimentary to this, the EU adopted a Strategy on Hydrogen in 2020, presenting a vision for the creation of a European hydrogen ecosystem in line with the Green Deal. This strategy recognises that hydrogen has a strong potential to bridge the decarbonisation gap that renewable energy cannot completely fulfil.

1 IEA (2023). Global Hydrogen Review 2023

2 European Commission (2020). Powering a climate-neutral economy: An EU Strategy for Energy System Integration

Russia's invasion of Ukraine and the resulting consequences for the European energy security influenced the EC's proposal of the REPowerEU plan. This plan primarily aims to reduce the dependency on Russian fossil fuels whilst staying aligned with a sustainable, affordable and secure transition.[3] This plan included ambitious hydrogen targets (10 Mton of domestic production and 10 Mton of imports) by 2030. Hydrogen is envisaged as an energy vector well-suited to store large amounts of renewable energy for different flexibility timescales of flexibility, alongside with small to medium back-up technologies (e.g. batteries, pumped hydro storage). Hydrogen can also be transported to connect production locations to more distant demand centres.[4]

In this European policy-making environment, hydrogen storage can play a crucial role in enabling a fully integrated system whilst supporting the development of a clean hydrogen ecosystem, and the decarbonisation of European energy systems overall. Underground hydrogen storage (UHS) is key to reach the EU's ambitious targets for the usage of clean hydrogen in various sectors, and it enables the deep decarbonisation of electricity systems. Hydrogen storage allows for a decoupling of hydrogen supply and demand, consequently ensuring both a stable supply to hydrogen off-takers and facilitating the integration of (fluctuating) hydrogen imports. Consequently, hydrogen off-takers are able to buy the most affordable hydrogen available.

An ideal solution for long-term European network flexibility needs

Regarding the electricity system, hydrogen storage facilitates the integration of renewable energy sources (RES) and provides both short- and long-term flexibility in balancing these intermittent energy sources. In this context, hydrogen is often considered a power-to-gas (PtG) tool to store electricity. UHS is the only tool that provides capacity to store large volumes of electricity and that can meet various seasonal demand. UHS can provide security of supply (SoS) to the electricity system, as it both creates electricity demand for the production of hydrogen and is later able to make it available as a fuel in power generation to back up intermittent RES production.

UHS can cover the flexibility needs of energy systems, ranging from one or several days to weeks (e.g. providing a viable solution to bridge the so-called "Dunkelflaute"), months (covering seasonal demand swings) and even years (providing security of supply). To unlock these benefits, smart energy system planning across Europe and energy vectors is key, and the role of large-scale hydrogen storage in addition to power-to-gas-to-power (PtGtP) must be acknowledged. More details on the role and benefits of hydrogen storage are provided in chapter 3.

3 European Commission (2022). REPowerEU, Affordable, secure and sustainable energy for Europe

4 European Commission (2020). A hydrogen strategy for a climate-neutral Europe

UHS as a key element of an efficient EU hydrogen market

When we further zoom in on the European policy landscape related to hydrogen, there are two important dossiers that provide a regulatory framework for the production of hydrogen: the Hydrogen and Decarbonised Gas Market Package ("Gas Package"), and the Delegated Acts of the Renewable Energy Directive (RED) II. Whilst the former defines rules and ambitions for an integrated European hydrogen market, the latter defines sustainability criteria for RFNBOs (renewable fuels of non-biological origin) i.e. sets out production criteria for green hydrogen. All these legislative files have contributed to critically de-risk the whole hydrogen value chain, and significantly increased investment security. Nevertheless, they fail to fully address the positive impact and the specific challenges related to the deployment of UHS in Europe.

The purpose of the Gas Package, currently in the final stages of the EU law-making process, is to boost the European production, infrastructure, transport, trade, and supply of renewable and low-carbon gases, including hydrogen. With this revision, the EU intends to kick-off a competitive decarbonised gas market, as well as enabling the development of cross-border and cost-effective hydrogen infrastructure. It defines and governs the transmission, distribution, supply, and storage of hydrogen, and among other areas, sets rules for third-party access (TPA) and injection tariffs.

Through the adoption of two Delegated Acts (Articles 27 and 28 of RED II.[5]), the EC has defined the sustainability criteria to produce hydrogen, which covers for instance temporal and geographical correlation of electricity that is used to produce hydrogen. These criteria are applicable to the transport sector and industry.

5 The Commission adopted the draft text of these Delegated Acts on 13 February 2023, and they were published on 20 June 2023. Both Delegated Acts entered into force – unchanged from the draft text – on 10th July 2023.

Ambitious EU hydrogen goals increase the necessity for UHS

On top of this, there are several EU policy dossiers that strongly impact the demand of hydrogen and define concrete hydrogen consumption ambitions for various sectors. Considering that demand and production of hydrogen is envisioned to scale up rapidly in next few years, impactful provisions facilitating the development of UHS must equally be considered.

The most important regulatory files actively encouraging an increased hydrogen consumption are the following:

» **RED III:** The revision sets out binding, step-by-step and sector-by-sector targets for the share of renewable energy sources (RES) in gross final energy consumption. The binding 2030 target was increased to a minimum of 42.5%, up from 32%. The RFNBO share for hydrogen used in industry shall reach 42% by 2030 and 60% by 2035, and reach at least 1% by 2030 in the transport sector.

- **REFuel EU Aviation:** The file sets out a mandatory blending obligation on jet fuel suppliers for Sustainable Aviation Fuels (SAF): 2% by 2025, increasing stepwise towards 34% by 2040 and 70% by 2050. A dedicated sub-target for synthetic fuels derived from green hydrogen is set: 1.2% by 2030, increasing to 35% by 2050.
- **FuelEU Maritime:** The regulation introduces mandatory GHG reduction obligations for shipping companies; the GHG intensity of energy used onboard of ships is to be reduced by 2% by 2025, up to 31% by 2040 and 80% by 2050.

Industry-driven pilot projects reveal the full decarbonisation potential of UHS

When relating the role of hydrogen storage in the European energy system to policy dossiers for the hydrogen market and the targets for hydrogen demand, the need to scale up hydrogen storage in Europe becomes clear. Several storage operators in Europe have already taken ambitious first steps by launching pilot projects to determine UHS' full decarbonisation potential as well as prove its technological feasibility.

Currently, there are around 40 pure-hydrogen UHS projects in development in Europe which will assure 22.1 TWh of pure hydrogen storage by 2040.[6] These projects are being developed by various infrastructure operators – a large part of which are represented in the H2eart consortium – and are in different stages of maturity and scale. Most of projects plan to operate with pure hydrogen, however, this 22.1 TWh would increase when also adding up projects that integrate various blends.

The predominant technological solution is salt caverns, but projects that intend to store hydrogen in depleted gas fields or aquifers are also being developed. All projects are spearheaded by infrastructure operators capable of developing large projects and accelerating the decarbonisation of energy systems. More details on the state of hydrogen storage projects will be provided in chapter 4.

Rapid action needed to assure investment security and unlock the necessary scale-up of UHS

However, the previously mentioned project list also includes various pilots and demonstration projects that are of a limited size. To support the development of a net-zero energy system in Europe, storage volumes need to be scaled up increasingly rapidly by 2030. Estimated volume requirements vary in different studies and range from 10s to 100s of TWh in 2030.[7,8,9] As lead times to develop UHS are very long (up to 10 years)[10], there is an urgent need to further detail these needs, and kick-off concrete plans and developments as soon as possible. More details on typical project timelines for hydrogen storage will be provided in chapter 3.

6 Hydrogen Infrastructure Map (2023). Hydrogen storage sites (Last updated in Q4 – 2023)

7 Gas Infrastructure Europe (2021). Picturing the value of underground gas storage to the European hydrogen system

8 Gas for Climate (2023). Assessing the benefits of a pan-European hydrogen transmission network

9 To be published by Gas Infrastructure Europe (2023).

10 Gas Infrastructure Europe (2021). Picturing the value of underground gas storage to the European hydrogen system

To enable an EU-wide UHS scale up, a stable investment and policy framework will be required as soon as possible. Until a financing and remuneration model for hydrogen storage is developed on a European level, it is unlikely that hydrogen storage projects develop at the required rate and scale because incentives and de-risking mechanisms are lacking. Legislation should enable the swift scale-up of a hydrogen storage business and market models, including financial support and increased investment certainty.

The necessity for a hydrogen-specific approach to storage

The future model for hydrogen storage could differ from the traditional model for natural gas storage. These differences must be accounted for in the policy-making process by ensuring a tailored approach to hydrogen, and hydrogen storage.
For instance, it should be accounted for that hydrogen has a lower energy content than natural gas, and seasonal spreads of hydrogen could be different than for natural gas. Also, the security (of supply) value of hydrogen storage assets needs to be recognised and properly monetised to create a viable business model.[11] Hydrogen users, for instance in industry, will be looking to buy hydrogen at the most competitive price. Hydrogen storage can contribute to this, as recent tests conclude that smart hydrogen storage integration in the electricity market can help reduce the cost for hydrogen production between 25-40%.[12]

11 Gas for Climate (2022). Action plan for implementing REPowerEU

12 Vattenfall (2023). HYBRIT: Hydrogen storage reduces costs by up to 40 per cent

02
Future-proofing the energy system with underground hydrogen storage

Key takeaways

UHS supports the flexibility needs of the future energy system and provides an essential link between the power sector and the hydrogen economy. A future energy system reliant on volatile electricity production of RES and demand fluctuations is in utmost need of flexible dispatchable backup, currently not yet provided.

Providing short to long term flexibility needs and a large spectrum of capacities, underground hydrogen storage is the sole techno-economically viable technology available. UHS in combination with PtGtP mechanisms can provide the necessary high flexibility needs whilst offering an incomparable scale of volume.

UHS unlocks benefits along the entire value chain and foster the development of RES. By implementing large-scale storage into an integrated energy system, investment and operational cost can be reduced whilst increasing the RES content in the energy mix, leading to lower emissions for a sustainable future.

2.1 Underground hydrogen storage is key for unlocking a resilient and decarbonised Europe

2.1.1 | Renewable energy sources increase flexibility needs

In most EU member states, the shift towards decarbonising the electricity system primarily hinges on expanding intermittent RES generation capacities such as wind and solar PV. This expansion accentuates the necessity for dispatchable backup given the heightened intermittency of generation. The inherent volatility in electricity production from renewable sources influenced by weather conditions and time of day results in unpredictable spikes and drops in power output.

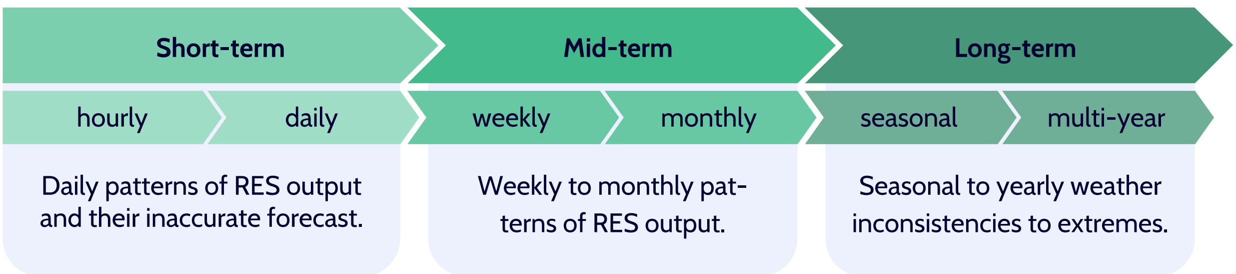
Managing these fluctuation demands stable and dispatchable backup generation, alongside an uptick in demand-side responses to synchronise electricity generation with demand. According to the EC's Joint Research Centre[13], flexibility needs are anticipated to rise across various timeframes — daily, weekly, monthly, and seasonally, depicted in Figure 1 – as RES network integration increases. Flexibility is particularly crucial due to the interplay between volatile electricity production and demand.

The management of volatile electricity production and similarly volatile demand lies at the heart of the flexibility challenge in the power sector. Figure 1 explains how "Long-, Mid- and Short-term" flexibility needs occur. The volatility in electricity production refers to the unpredictable fluctuations in power generation from RES, such as wind and solar PV. On the other hand, volatile electricity demand denotes unpredictable changes in the amount of electricity consumed due to factors like weather, economic activities, or societal patterns.

In a renewable hydrogen ecosystem, where hydrogen is produced from renewable electricity, the same long- and short-term flexibility needs as in the electricity system are foreseen. Given the anticipated volatility in hydrogen production, industrial users, who are expected to be the first adopters of hydrogen and who have stable demand requirements may exhibit a relatively flat demand curve overall.

Figure 1

Types of flexibility needs in a renewable energy system



13 Koolen, D., De Felice, M. and Busch, S., Flexibility requirements and the role of storage in future European power systems, EUR 31239 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-57363-0, doi:10.2760/384443, JRC130519.

However, with the progressive substitution of natural gas and the expansion of hydrogen use across diverse sectors, more complex demand curves could significantly escalate the flexibility demand of a hydrogen system. To address this challenge, dispatchable backup generation becomes essential.

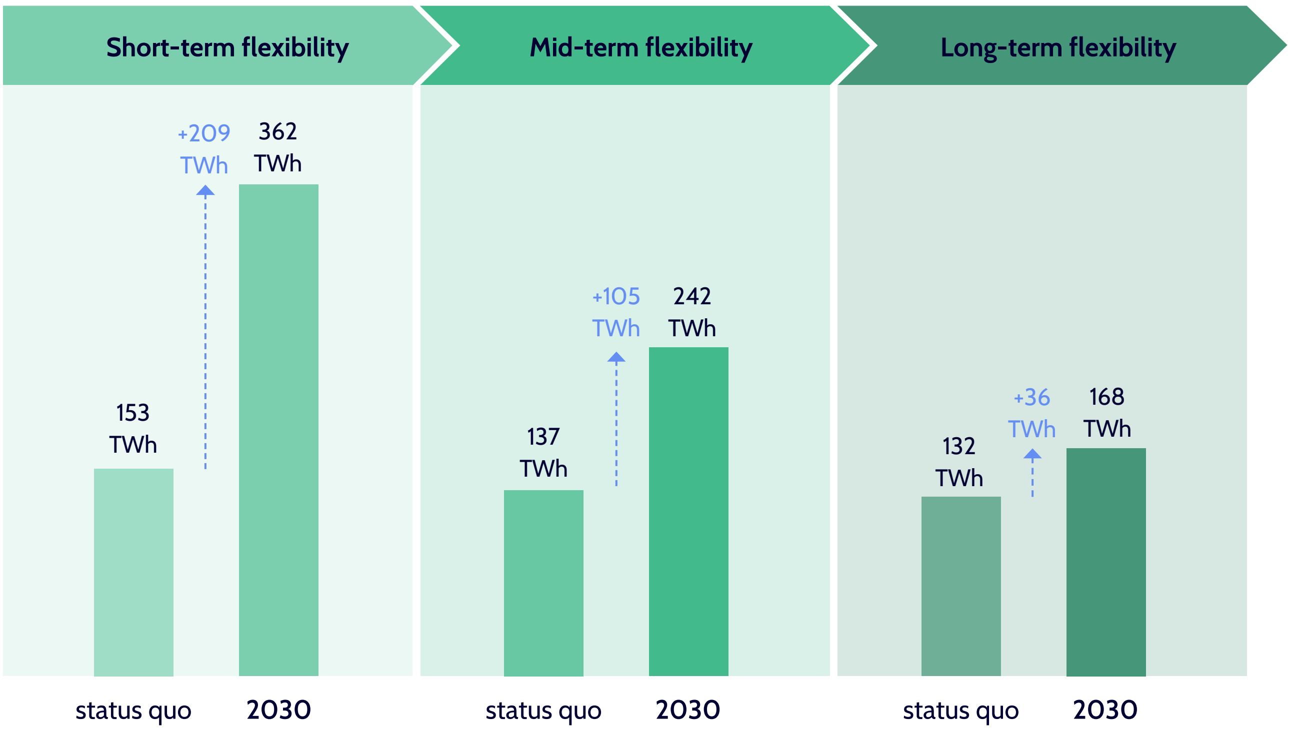
Back-up must include sources that can be readily adjusted to balance out demand variations or compensate for dips in renewable energy production. Additionally, demand-side response measures, where consumers adjust their consumption in response to grid signals, can contribute to the flexibility needed to harmonise the grid.

The aggregated flexibility requirements across sectors point to a substantial increase in the future within all flexibility types. Multiple reports highlight projections of a surge in flexibility needs by 2030, reaching over 200 TWh for short-term flexibility, 100 TWh for mid-term flexibility and almost 90 TWh for long-term flexibility, as illustrated in Figure 2.[14]

To achieve this, various flexibility solutions are needed as their availability and suitability for the specific demands of a net-zero energy system vary significantly, but an ideal solution would offer all flexibility types to minimise the build out quantities.

Figure 2

Annual flexibility needs for a future energy system in TWh[15,16]



Source: ACER

14 FTI-CL - Energy Economic analysis of the role for H2 SSO, 2023.

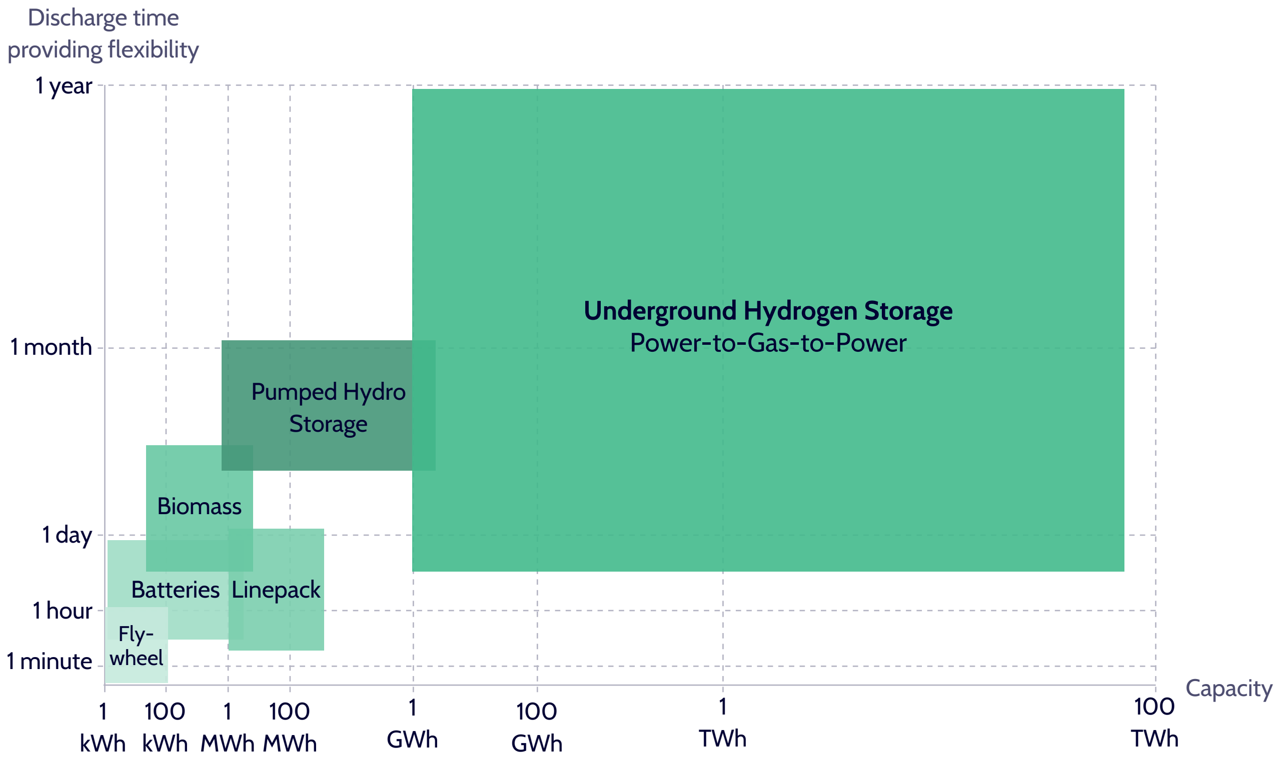
15 Flexibility solutions to support a decarbonised and secure EU electricity system [EEA/ACER Report 09/2023]

16 FTI-CL - Energy Economic analysis of the role for H2 SSO, 2023.

2.1.2 | An overview of flexibility solutions suitable for future energy system

Figure 3

Comparison of flexibility solutions in terms of discharge time in which they provide the according capacity[17,18,19]



Attention: Intervals on the capacity axis are exponential i.e. UHS can have almost 1 million times the capacity of a battery.

Varying flexibility needs can be covered by specific technological solutions. **However, as Figure 3 illustrates, UHS is a uniquely versatile storage solution which can provide flexibility specifically tailored to a wide range of use cases simultaneously. Thereby achieving benefits in multiple energy systems.**

Presently, flexibility is addressed within their respective systems. Specifically, gas and electricity systems have dedicated flexibility providers tailored to their unique requirements.

17 School of Engineering, RMIT University

18 Guidehouse internal analysis and expertise

19 FTI-CL - Energy Economic analysis of the role for H_2 SSO

Decarbonising gas systems using UHS

Since flexibility in the gas systems is currently facilitated by Underground Gas Storage, integrating this concept into the hydrogen system is a viable option. A widely debated topic is using "Linepack" as storage. A method to leverage the operational pressure ranges of the gas system and operate a pipeline on a higher-pressure level than average. While this incurs additional compression costs, it allows for additional short-term gas storage in pipelines, that only allows to balance minor supply-demand inconsistencies. The fact that linepack is not a feasible solution additionally underlines the advantages of UHS. Unlike natural gas systems where a stable supply is relatively assured, hydrogen system's volatile production conditions underscore the necessity of UHS alongside linepacking.

UHS is a game changer for integrating flexibility across energy systems as other solutions are limited in capacity.

For electricity systems, various flexibility options for dispatchable backup appear to be a viable solution. Options providing the needed storage for renewable energy systems differ significantly in operation and technical maturity. Most recognised flexibility options are pumped-hydro storage, fossil generation, biomass, and batteries. Figure 3 also identifies a clear lack of long-term flexibility solutions. This shows that flexibility solutions for the electricity system provide only the short- to mid-term flexibility and are limited in terms of capacity. Looking for a flexibility solution for electricity systems which meets future energy system needs rules out fossil fuel options, like coal, as they are not coherent with climate targets. Batteries are adequate to provide short term flexibility by storing relatively low volumes of energy with quick charge/discharge rate. Nevertheless, batteries fall short in providing long term flexibility due to limited energy storage and a low charge/discharge frequency. Moreover, the potential for large batteries is oftentimes contested by arguments related to the cost intensity or environmental impact of battery. Consequently, batteries will play a key role in future energy systems but are not able to deliver flexibility in the bandwidth needed. Remaining adequate options providing medium term flexibility, e.g. biomass or pumped-hydro storage, are technically viable options but not sufficiently scalable and geographically limited.

UHS can provide flexibility across a broad spectrum of use cases and stands out as a highly versatile storage solution. Enabled by an integrated energy system allowing to achieve benefits in both electricity and hydrogen systems, as electricity flexibility solutions could cover hydrogen flexibility needs and more important vice versa. That allows the electricity system to use the long-term flexibility provision solution of the gas system, meaning Underground Gas Storage. With PtGtP technologies, Underground hydrogen Storage shows its significance for both, the renewable gas system, and the electricity system, offering scalability and short-to-long-term flexibility, as illustrated in Figure 3.

2.1.3 | Underground hydrogen storages' versatile short- and long-term flexibility as a game changer

In the landscape of flexible delivery solutions, UHS paired with hydrogen-fuelled power generation (GtP), emerges as the sole techno-economic viable technology. This dynamic duo not only addresses long- and mid-term flexibility requirements crucial for deep decarbonisation in a high-RES share energy system, but also proves versatile in catering to short-term flexibility needs on an hourly basis.

UHS is pivotal for long-, mid- and short-term energy storage

The synergies between UHS and PtGtP technologies allow for a universal approach to flexibility, seamlessly spanning long-term, mid-term, and short-term storage requirements in the evolving landscape of decarbonised energy systems.

Underground Hydrogen Storage plays a pivotal role as a long-term storage option, necessary for coping with seasonal to multiyear weather fluctuations in European countries to balance out renewable energy production and usage. The studies mentioned in this report underscore the significance of UHS in an integrated energy system, especially when interconnected storages across Europe create synergies and needed UHS volumes for seasonal and long-term storage were identified. When examining Figure 4, it becomes evident that the seasonal operating pattern of hydrogen storages in 2050 resembles that of existing natural gas storage. During the summer, storage is filled up, and then emptied over the winter, synchronised with the availability of variable RES. This highlights the indispensability of underground storage for hydrogen to improve energy security year-round, similarly to gas.

UHS proves instrumental for mid-term flexibility, and essential for handling weekly to monthly fluctuations in RES production. These variations may be influenced by changing weather patterns, particularly evident in wind energy production where output varies from 0% during wind lulls, to 100% during weather extremes.

Figure 4

UHS applicability for all flexibility needs proven by research[20,21,22]

Short-term	Mid-term	Long-term
Project 'Hypster': Performing 100 cycles in 90 days.	GIE / Artelys: Territorial use case #2 of GIE study by Artelys (2022).	Seasonal storage pattern in the Gas for Climate (2023) study.

20 "Hypster" Project: D-1.3-Cycling-testing-program-definition

21 Gas Infrastructure Europe (2022) Showcasing the pathways and values of underground hydrogen storages – Final report

22 Gas for Climate (2023). Assessing the benefits of a pan-European hydrogen transmission network

UHS' positive impact on a low-carbon energy system must be underlined.[23] Figure 4 illustrates UHS's capability to balance supply-demand differences over two months. It emphasises the benefits of storing hydrogen when electricity prices are low and providing hydrogen during high-demand periods or when electricity prices are high. This allows UHS to act as a real alternative to fossil mid-term flexibility alternatives. Turning to hydrogen-based storage solutions instead of fossil ones not only reduces the carbon footprint but also maximises the utilisation of RES output during weekly changing patterns, leading to significant cost reductions.

Zooming in on the complexities of short-term flexibility, it becomes evident that UHS is also able to address hourly to daily fluctuations in energy production and usage while still providing large-scale volumes. The "HyStock" and "HyPSTER" projects serve as prime examples, as they illustrate how a salt cavern can facilitate up to hourly flexibility with high cycling rates. Latest research outcomes of this project confirm the ability to perform up to 100 cycles in 90 days, indicated in Figure 4 allowing flexibility provision on a daily base. This is made possible through the deployment of multiple wells at a single site, showcasing UHS's adaptability to the dynamic energy demands arising from day-to-night shifts, and the diverse patterns of energy demand from households and industries.

2.2 Underground hydrogen storage accelerates the integration of energy systems

The flexibility provided by UHS positively benefits actors along the entire hydrogen value chain. This includes RES and hydrogen developers and producers, transport, and distribution companies, as well as RES and hydrogen offtakers.

2.2.1 | How underground hydrogen storage can scale up hydrogen production

Within the domain of green hydrogen project development, the utilisation of UHS brings forth significant advantages. Efficiency gains are multifaceted, particularly in terms of investments in RES capacities. UHS allows for a more streamlined and cost-effective approach, aligning with the stringent temporal correlation criteria set by the EC. This not only enhances the cost-competitiveness of green hydrogen but also promotes a more resilient infrastructure.

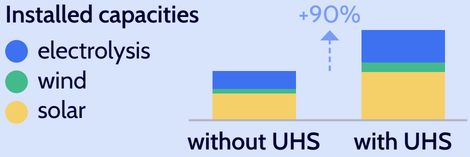
Furthermore, the reduction in grid connection requirements is a noteworthy outcome. Through more efficiently dimensioned RES capacities, UHS contributes to cost reductions and shortened lead times. The heightened security of green hydrogen supply emerges as a pivotal factor, rendering it a compelling alternative to grey hydrogen and traditional fossil fuels which currently benefit from physical backup.

23 See 21

Figure 5
Kick-start value for hydrogen supplier[24]

Kick-start value for H_2-supply

Underground hydrogen storage allows an optimisation of electrolysis and RES-source use of almost **double the amount of capacities** whilst **lowering the investment costs** significantly. Facilitating the emergence of a reliable hydrogen market.



Investment cost reduction of 4-36% based on a comparison between without and with UHS.

The kick-start value of UHS is particularly instrumental in overcoming the classic chicken-and-egg challenge in hydrogen adoption. By accelerating the deployment of clean hydrogen in industrial applications, UHS facilitates the emergence of a robust hydrogen ecosystem and with greater volumes achieves increasing value. Timely deployment becomes a crucial building block in resolving the demand-supply paradox, where demand materialises only when a reliable supply is available, and supply ramps up once demand is established.

Moreover, UHS plays a pivotal role in GHG reduction by curbing the curtailment of RES generation through the storage of excess electricity as hydrogen, not only a more sustainable energy system is promoted but also the full decarbonisation of electricity generation in systems marked by high-RES shares is enabled.

The arbitrage values associated with UHS are significant. By using RES electricity to produce hydrogen, and then utilising it during periods of limited or no RES generation, UHS contributes to inter-temporal arbitrage. This strategic utilisation reduces the variable cost of green hydrogen production, further solidifying its economic viability.

2.2.2 | Underground hydrogen storage increases resiliency of TSO and DSO operation

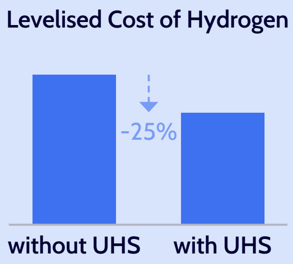
Examining the Levelised Cost of Hydrogen (LCOH) underscores the advantages UHS brings to midstream players. **For electricity TSOs and DSOs, UHS facilitates a more efficient build-out of RES capacities for green hydrogen production in the mid-term. This strategic alignment reduces the need for extensive grid expansion, prevents bottlenecks and ensures that UHS availability coincides with clean hydrogen usage targets.**

24 Gas Infrastructure Europe (2022) Showcasing the pathways and values of underground hydrogen storages – Final report

Figure 6
System value provided by UHS[25]

System value for H_2-transport

UHS **reduces the production cost** of hydrogen by more efficient use of the systems, enabling more economic operation of electrolytic hydrogen sources. Making the future **energy systems reliable and resiliant** whilst decreasing the need for fossil-sourced back-up.



The systemic value of UHS is not to be underestimated. Firstly, UHS streamlines the build-out of RES generation capacities, which – in turn – facilitates meeting the growing demand for green hydrogen and minimises the expansion needs of electricity grids. Secondly, UHS reduces the overall need for energy infrastructure build-out by providing an alternative decarbonised vector: hydrogen. Repurposing existing transport and storage infrastructure could result in reduced capital costs associated with green hydrogen production.

UHS also critically increases the security of electricity supply. By providing hydrogen as a backup fuel for RES generation, UHS ensures the resilience of the energy system which may be negatively impacted by everchanging weather and climate events. This increase in insurance value is quantifiable and equals the present value of expected losses due to electricity supply interruptions, and the associated costs of emergency remediation measures.

2.2.3 | Underground hydrogen storage ensures resource-efficient decarbonisation measures

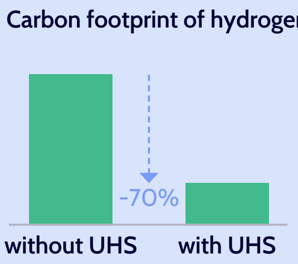
The downstream benefits of UHS extend to societal and industrial realms, with a focus on CO2 emissions. From a societal standpoint, UHS contributes to a reduction in investments needed for energy system decarbonisation. By enabling a more efficient build-out of RES and electrolysers, UHS minimises the need for extensive grid connections and expansions. The inherent security of electricity supply, even in deep decarbonisation scenarios, aligns with broader climate targets.

25 Gas Infrastructure Europe (2022) Showcasing the pathways and values of underground hydrogen storages – Final report

Figure 7
Environmental value for hydrogen offtake[22]

Environmental value for offtakers

UHS allows offtakers to achieve the climate targets by e.g. decarbonising their industrial processes with more renewable hydrogen. Integrating UHS reduces the need for fossil generation leading to a reduction of hydrogen's carbon footprint by over 70%.



For industrial end-users, UHS emerges as a facilitator of cost-effective green hydrogen production and availability. Its support for efficient RES build-out and the assurance of a secure clean hydrogen supply across diverse applications is pivotal. The insurance value of UHS becomes tangible in protecting against disruptions in clean hydrogen production or imports by storing hydrogen in proximity to demand centres. Furthermore, UHS enhances the resilience and optionality of the energy system by enabling the use of clean hydrogen in diverse applications, thus reducing expected losses and costs associated with emergency remediation measures.

The environmental value of UHS is underscored by its role in the accelerated transition from grey hydrogen and other fossil fuels to clean hydrogen. By avoiding emissions in industrial and transport applications, UHS plays a vital role in achieving sustainable and environmentally friendly energy systems. Its multifaceted contributions echo not only economic viability but also a commitment to environmental stewardship and long-term energy sustainability.

03
Development of underground hydrogen storage assets

Key takeaways

To unlock all benefits of UHS and leverage synergies, various technological UHS solutions must work together. All storage types have their individual advantages whilst being simultaneously constrained by either geographical or technical properties. When connected via pan-European infrastructure, all advantages can be leveraged, and boundaries overcome.

Rapid kick-off of UHS development whilst ensuring high safety standards is of utmost importance. SSOs have the technical experience to develop status-quo gas storage infrastructure, enabling hydrogen storage assets to utilise their full potential in flexibility provision whilst also being aware of possible never faced safety precautions.

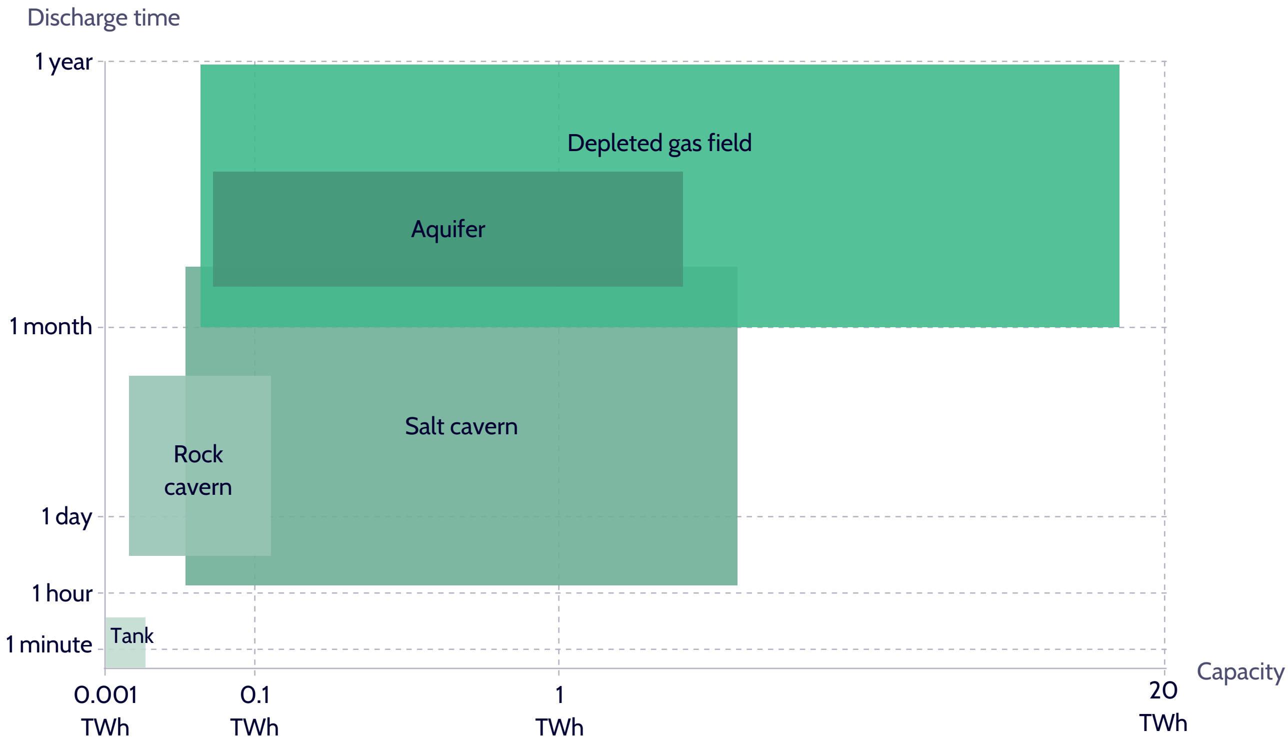
Building on decades of experience and leveraging existing infrastructure shortens development timelines and investment needs. UHS is a scalable technology as existing underground gas storage can be repurposed for the use of hydrogen, reducing development time and consequently ensuring a faster achievement of benefits.

3.1 All storage types are needed to achieve system benefits

To unlock the paramount benefits of UHS, it is crucial to delve into the distinct roles played by various storage types and comprehend how their simultaneous development contributes to a synergistic effect, unlocking the complete bandwidth of UHS capabilities. In the realm of underground hydrogen storage, distinctions in size, withdrawal and injection rates, cycle capacity, and repurposing maturity are evident among storage types. The types currently under discussion for hydrogen storage are salt caverns, depleted gas fields, aquifers, and rock caverns. Additionally, it must be noted that while above ground storages (i.e. tanks) are also available for short-term storage provision, there are in no noticeable dimension for infrastructure relevance due to limited storage volume.

Figure 8

Comparison of UHS types in terms of capacity and discharge time (flexibility type)[26]



Attention: Intervals on the capacity axis are exponential i.e. UHS can have almost 1 million times the capacity of a battery.

26 Gas Infrastructure Europe (2021). Picturing the value of underground gas storage to the European hydrogen system

Salt caverns are artificial structures constructed within underground rock salt formations, and have become crucial in the search for efficient hydrogen storage. The process of creating these caverns involves injecting water underground to dissolve the rock salt, resulting in extracted brine and a completely enclosed underground cavity. This unique feature allows salt caverns to serve as reliable storage unit for hydrogen, a role proven across various global locations. Typically having a single well per cavern for both injection and extraction, salt caverns show injection and withdrawal rates, capable of up to 10 cycles per year. Despite often having lower overall capacity, they find a role as peaking storage facility in the natural gas system. Some installations extend their utility to seasonal storage, utilising multiple caverns to meet demand variations. But limits on injection and withdrawal rates are only dictated by well infrastructure throughput and surface installation design. Initial findings indicate that deploying multiple wells in proximity enhances injection and withdrawal rates, enabling even hourly dispensing. These unique characteristic positions salt caverns as agile contributors to peak shaving and fulfilling hourly storage needs. While salt caverns are a promising storage type for hydrogen, the geographical availability of salt caverns is constrained primarily to northern central European countries.

Depleted gas fields, having contained hydrocarbons for millions of years, now serve a crucial role in energy storage. Comprising approximately 64% of the EU-27 and UK's natural gas storage capacity, these underground structures have been repurposed for decades to meet storage demands. In contrast to salt caverns, the utilisation of porous rock structures for injection and withdrawal is constrained by rock permeability. Despite this limitation, these reservoirs possess substantial gas-holding capabilities, often accommodating several months' worth of demand. Typically undergoing two annual cycles of injection and withdrawal due to the time-intensive process, they are pivotal for large-volume seasonal storage, with some instances showcasing their adaptability for shorter-term flexibility. The potential transition to hydrogen storage is a promising prospect for these reservoirs. Their historical competence in storing gas for extended periods suggests a capacity to accommodate hydrogen, aligning with evolving energy needs. Noteworthy advantages include their volumetric superiority over salt caverns and a well-established geological understanding derived from their extensive operation in central Europe for natural gas storage. Due to the nature of depleted gas fields, storing hydrogen is more complicated and differs from one field to another, and more research must be done on this topic.

Alike depleted gas fields, **aquifers** are porous sedimentary rock structures filled with water instead of natural gas, that show potential for hydrogen storage. Successful demonstrations in depleted fields suggest the feasibility of utilising aquifers for hydrogen storage.

Hard rock caverns represent the newest addition to underground storage technologies. Like salt caverns, they are artificial structures, but carved into metamorphic or igneous rock. While likely suitable for hydrogen, their costliness positions them for specialised use reserved for peaking facilities in regions lacking alternative storage options.

The integration of all storage types in a European Hydrogen network ensures the simultaneous utilisation of their diverse capabilities. The interplay between salt caverns and depleted fields exemplifies the importance of a diverse portfolio of storage types within the UHS landscape. Their simultaneous development not only addresses specific regional needs but also contributes collectively to a robust and flexible hydrogen storage infrastructure. In the broader context of a European Hydrogen network, these varied storage options should be combined to maximise their positive impact and overcome geographical constraints.

In conclusion, the development of all storage types in parallel is vital to fully unlock the potential of (repurposed) underground hydrogen storage and not hindering its immediate implementation.

3.2 Technology readiness ensures swift deployment

Repurposing existing gas infrastructure and leveraging decades of experience operating them ensures safe and reliable development of underground hydrogen storages in the coming years. To meet the flexibility needs of a very dynamic hydrogen market, site-specific adjustments must be made. Site-specific alterations need to be thoroughly tested, and assess the different properities of hydrogen compared to natural gas, as well as the impact on the operational and safety-related design of surface and subsurface technology. Many UHS projects are currently being carried out at European and national level to further investigate and analyse the necessary changes in plant design and layout to meet necessary standards.

3.2.1 | Importance of injection and withdrawal capacities to meet flexibility needs

The key parameters for storage operation are the cushion gas volumes, working gas volumes, injection rates, and withdrawal rates. Cushion gas refers to the gas permanently stored in the underground structure during the lifetime of the site and its main function is to maintain the conditions required for adequate storage operation. Working gas is the amount of gas that can be injected into and withdrawn from the storage in one cycle. Injection and withdrawal rates determine the maximum gas flow rate in and out of the asset. Gas storage operators offer a variety of products to serve the different needs of the market. Typically, these come as storage bundles — a combination of working gas volume, injection, and withdrawal capacities with a fixed ratio between these three. Each storage asset has a defined churn rate (i.e. how often can injection or withdrawal occur within a year).

SSOs have defined products for a variety of timescales, divided generally into seasonal churn, mid churn, and fast churn products depending on the specific client requirements. Netting of injection and withdrawal requests from customers reduces the actual, physical need for storage operation mode, which allows for more flexibility to react to the fluctuating supply and demand conditions, especially for fast churn products.

Long-term storage products typically have lower withdrawal rates that last for months, requiring large storage volumes, and are designed to meet seasonal variation in hydrogen demand (e.g. higher demand in the winter than summer due to more heating demand). Mid-term products have higher cycling rates with medium-sized volumes, depicted in Figure 9.

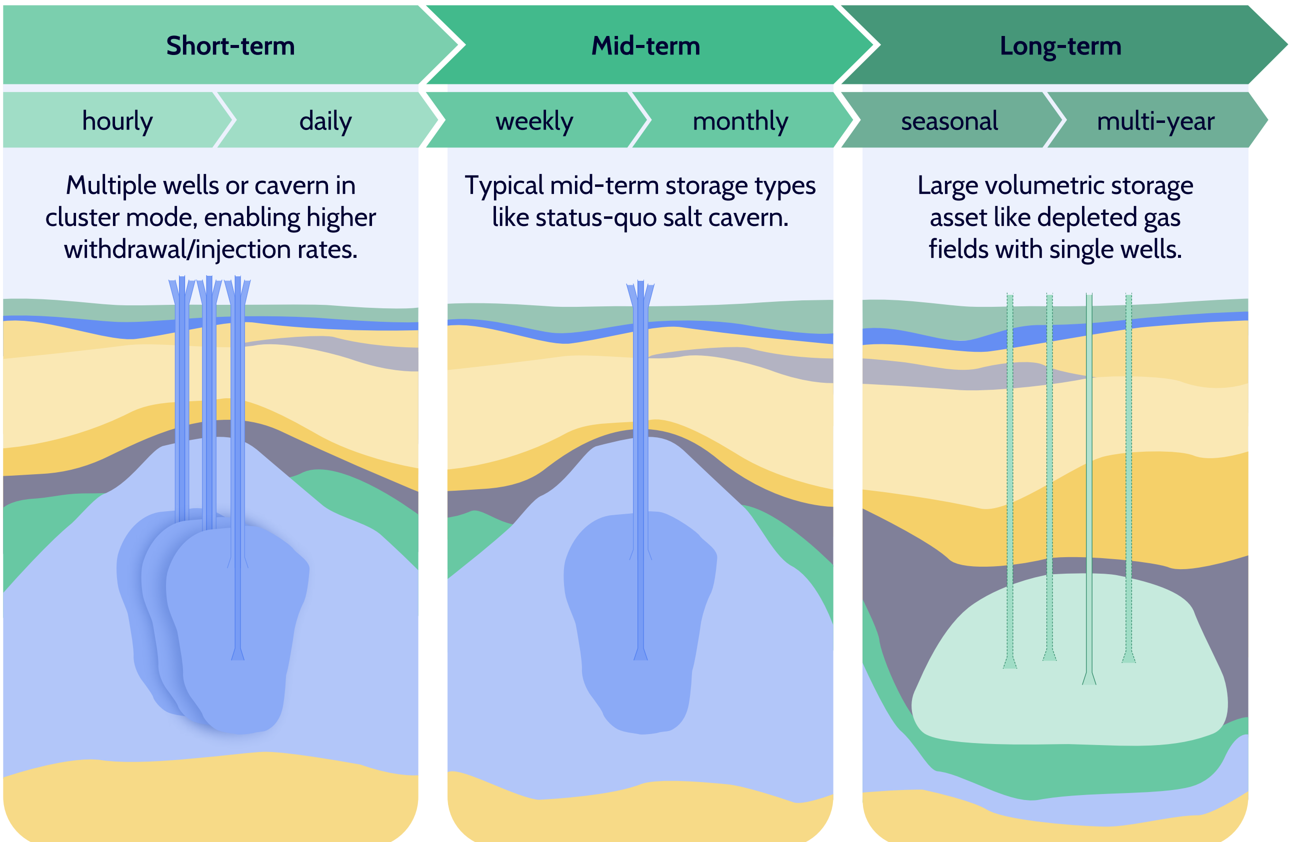
As shown in Figure 9, some storages also have multiple wells for one cavern or are operated in a cluster mode (multiple storages next to each other), allowing different cycle types at the same time. Hence injection and withdrawal services could be separated shortly in time, allowing a high flexibility option for short term needs.

It is important to understand, that for the needed flexibility provision, not only the working gas volume is important but also the withdrawal and injection rates, as they are heavily influenced by the type of operation and product they serve. In the future energy system injection capacity becomes a crucial pillar to fit to RES production in the electricity system while ensuring at the same time the continuous availability of hydrogen as an energy carrier.

Figure 9

Potential setup of UHS to serve the full flexibility range by efficient well placement to increase withdrawal and injection rates

Note: All technologies can be utilised for various flexibility ranges (e.g. salt caverns can provide long-term storage). Drawings are not representative of true size, depleted gas fields are significantly larger.



3.2.2 | Repurposing existing underground assets for hydrogen storage

When it comes to repurposing existing gas infrastructure, general feasibility with bespoken storage types is a given and only operational differences to natural gas, particularly in terms of compression need to be considered.

Hydrogen flows faster due to its low density and exhibits a negative Joule-Thomson effect, wherein it heats up during expansion and cools down during compression. This contrasts with natural gas, which, like air, heats up on compression and cools down on expansion. The negative Joule-Thomson effect in hydrogen has implications for the design of storage systems and compressors under high pressure.

Therefore, the conversion of natural gas storage facilities into hydrogen storage facilities or the development of new storage facilities will require safety concepts for the permitting process. It is therefore necessary to take a holistic view of all relevant aspects and to develop and implement appropriate safety concepts and measures, to ensure the safety of UHS facilities. The safety aspects specific to underground storage facilities will be fully covered by the approval procedures. In addition, the experience, and findings from existing or planned UHS projects will be used to promote and support the development of technical standards and regulations in a close professional and technical collaboration between the various involved parties. Decades of experience with the storage of natural gas have shown that hydrogen can be safely stored underground. Building on this experience, large volumes of hydrogen will continue to be stored and withdrawn safely and flexibly in underground storage facilities in the future.

3.3 Significant development timeline challenges

Understanding the constraints associated with rapid development for safety reasons, as well as recognising the crucial role of effectively integrating various storage types with their specific adjustment needs, highlights the key to unlocking maximum flexibility provision. This underscores the necessity of simultaneously advancing all types of storage as soon as possible, taking into account diverse timelines for a swift and smooth development to reach the targets for 2030.

3.3.1 | Typical development timelines of underground hydrogen storage

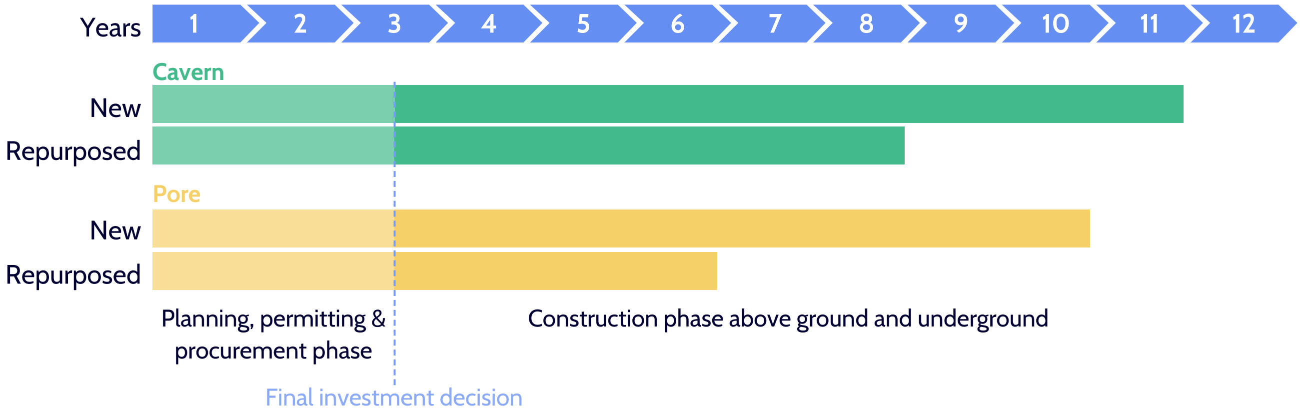
The development of underground hydrogen storage encompasses distinct phases, each crucial to the overall timeline. Initially, an open season or market consultation phase is initiated to thoroughly assess and understand the storage requirements. This phase serves as a foundation, gathering essential insights for subsequent decision-making.

Following this, the planning, permitting, and procurement phase ensues, a comprehensive stage that involves meticulous planning, obtaining necessary permits, and managing procurement processes. On average, this phase spans approximately 2.5 years and lays the groundwork for the subsequent stages of development.

Upon reaching the Final Investment Decision (FID), the actual construction phase kicks in. This stage varies based on factors such as storage types and whether the facility is newly constructed or repurposed from natural gas use. Figure 10 illustrates that repurposing can notably reduce the construction time by over 2 years, showcasing the potential impact of prior infrastructure.

Figure 10

Development timeline of UHS[27,28]



In total, the entire development timeline ranges from 6 to 11 years. It's important to note that the duration can be shortened, especially during the permitting phase. Acceleration in the regulatory framework is a key determinant in accelerating the overall development process. This crucial aspect, focusing on regulatory acceleration, is delved into more deeply in chapter 4, shedding light on strategies to streamline the permitting phase and enhance the efficiency of Underground Hydrogen Storage projects.

3.3.2 | Cost and business case for underground hydrogen storage

In the pursuit of developing the necessary flexibility in energy storage, substantial investments become imperative, whether through repurposing existing facilities or constructing new storage assets. The construction costs associated with underground storage are multifaceted, encompassing cushion gas, site exploration and development, compressors, as well as various surface and subsurface infrastructure elements.

Recent research, illustrated in Figure 11, underscores the diverse nature of these cost components, spanning from anticipated 450 €/MWh to 1200 €/MWh. It's crucial to acknowledge the challenge in generalising storage costs due to the wide spectrum of storage sizes, operating conditions, and the frequency of injection and withdrawal cycles. Rather than serving as a basis for direct comparison, the cost analysis should be viewed as an indicator of the order of magnitude concerning the overall investment and levelised cost of Underground Hydrogen Storage (UHS).

27 INES (2023) Positionspapier Vorschlaege-Marktrahmen Entwicklung-H2-Speicher

28 FTI-CL - Energy Economic analysis of the role for H_2 SSO

Figure 11

Potential investment costs for types of UHS[29]

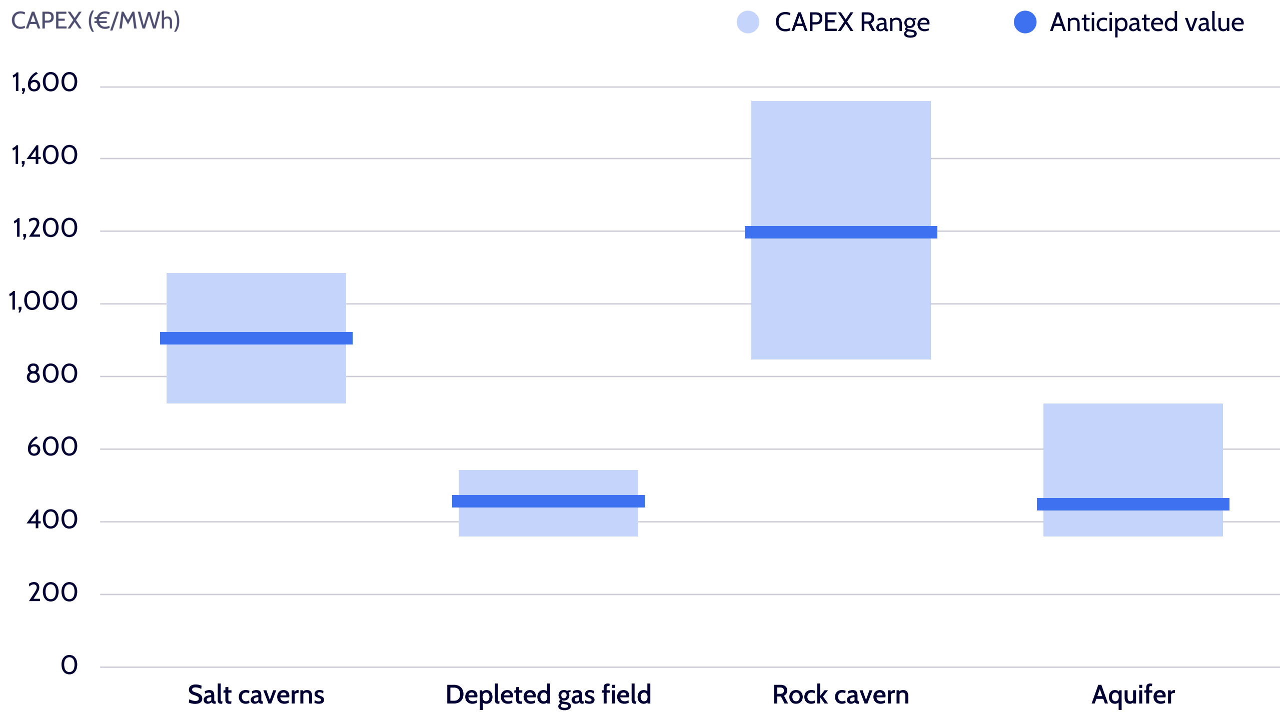


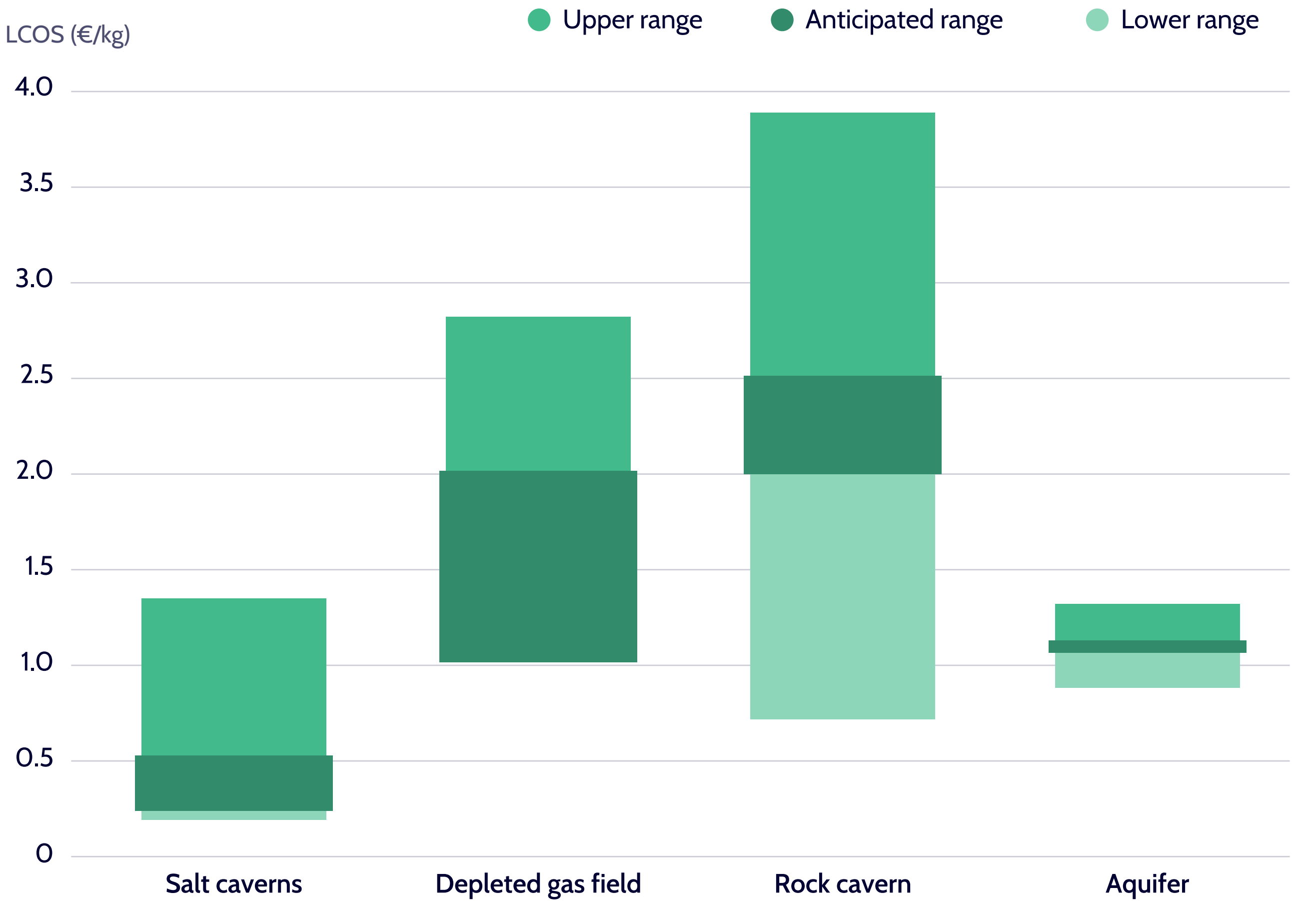
Figure 12 shows cost estimates, derived from literature, relying on assumptions about storage specifics and operational parameters such as the number of cycles. These factors significantly influence the calculated Levelised Cost of Storage (LCOS). Notably, UHS emerges as the most cost-competitive technology for both long-term electricity and hydrogen storage. The chapter concludes by identifying the key components essential for establishing a viable business case in the realm of underground storage. It emphasises the necessity for substantial upfront investments (CAPEX), recognising the current absence of investment certainty. Despite this, these investments return benefits, not only in operational terms but also in economic gains, thereby forming a compelling business case for potential investors. Additionally, the discussion sheds light on the inadequacy of existing subsidy mechanisms for UHS development. This prompts a deeper exploration of the policy overview, linking the discussion to the broader landscape of energy policies.

29 Based on input of H2eart for Europe alliance members.

Figure 12

Comparison of LCOS depending on storage type[30,31]

Note: The below graph should not be seen as a comparison between different types of storage, that would be too premature. Rather, the graph provides an indication of magnitude of investment and levelised cost.



30 Gas Infrastructure Europe (2021). Picturing the value of underground gas storage to the European hydrogen system

31 FTI-CL - Energy Economic analysis of the role for H_2 SSO

04
Trajectory of underground hydrogen storage developments: 2030 and beyond

Key takeaways

There is a large gap between planned hydrogen storage projects and needed storage volumes for the benefit of the EU energy system. In 2030, this gap is predicted to measure 36 TWh. By 2040 and 2050 this gap will have increased significantly due to large uncertainties in the market regarding the development of underground hydrogen storage projects.

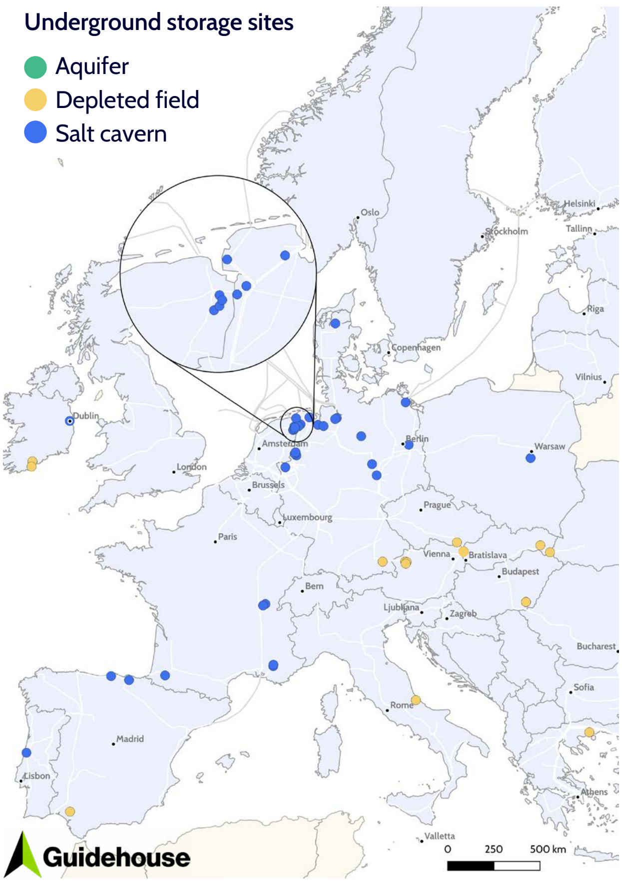
This storage gap means there is a need for €18-36 billion in additional investment by 2030, and this gap is only expected to increase towards 2040 and 2050. These large investments, typical for large infrastructure projects, are needed to unlock all previously mentioned benefits for both the electricity system and the hydrogen ecosystem e.g. efficient integration of renewables and a stable supply of hydrogen.

Narrowing the storage gap requires a clear and transparent regulatory framework to facilitate investment decisions. Public financial support is needed from the EU and national funds. Storage developers need the right (financial) support to scale up assets and develop more mature and suitable projects.

4.1 Acceleration of UHS projects is needed to reach required 2030 volumes

Hydrogen storage project developments are a necessity for the future energy system in Europe, and an accelerated trajectory is possible. As described in chapter 3, there is a significant role to play for UHS in the future energy system with large hydrogen storage volumes. This role of hydrogen storage in the energy system is twofold, supporting both the electricity system through RES integration and flexibility, and the hydrogen economy by providing a secure and affordable supply. However, as described already briefly in chapter 1, the development of large-scale hydrogen storage requires significant efforts and lead time.

Figure 13
Map of UHS projects planned to be operational across Europe by 2030[33]



In practice, there is a large group of organisations that are moving into the hydrogen storage market, and the founding members of this Alliance are among the storage operators that are leading the way within Europe.

Storage projects are already being developed across different geographies, covering different technologies. Recently, a group of organisations led by ENTSO-G has published an update of their Hydrogen Infrastructure Map. This map includes around 50 hydrogen storage (pilot) projects to be commissioned from now towards 2040. The projects differ across the following parameters:

- Project type: new assets, the conversion of existing assets or a mix of both.
- Technology: Salt caverns, lined rock caverns, depleted gas fields, aquifers, and surface storage.
- Maturity: From projects that are less advanced to projects that have already taken final investment decisions.
- Size: Varying in working volume between pilot (MWh's) to large-scale commercial scale (TWh's).
- Operating mode: Some storages are intending to (at first) use hydrogen blends, while others are planning to only inject and withdraw pure hydrogen.

33 Hydrogen Infrastructure Map (2023). Hydrogen storage sites (Last updated in Q4 – 2023)

The members of this alliance are involved as partners in around half of these projects, leading the way for storage development in Europe. When adding up all currently planned projects in this database, this leads to a total storage capacity of 9.1 TWh for pure-hydrogen storage in 2030, and around 22.1 TWh in 2040. Most of projects plan to operate with pure hydrogen, however, these 2030 and 2040 numbers would increase when also adding up projects that integrate various blends.

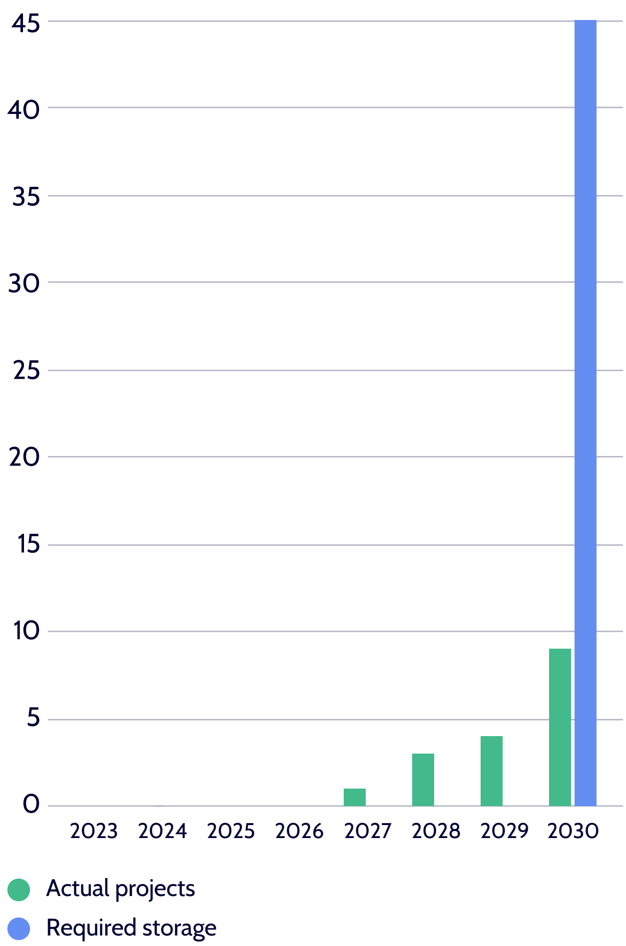
In Figure 14, this is visualised and related to the required storage volume for the benefit of the European energy system based on various industry reports as described in chapter 1. The graph gives a clear signal that there is a gap between planned large-scale storage developments and optmimal required volumes, while it implies that this gap is only going to increase after 2030.

The hydrogen storage landscape will be a mix of salt caverns, depleted gas fields, aquifers and rock caverns. The largest part of the storage volumes in 2030 will be in salt caverns (around 2/3), while depleted gas fields have the potential to further scale storage capacity. Storing hydrogen in depleted gas fields is more complicated and requires more research. Also, there are a few very small storage sites in 2030 that plan to store hydrogen in lined rock caverns. This is a new and potentially important technology option, as they can be located across the continent, overcoming geographical constraints of the other storage media. After 2030, also storage in aquifers is expected to lift off, however this storage technology has lower potential due to challenging geological constraints.

When zooming in on the year of 2030 (Figure 15), the required storage volume is 40-50 TWh based on estimations by GIE.[34] Compared the midpoint of this with the current project outlook, this results in the need for a 395% increase in storage capacities in six years. With significant lead times and a highly uncertain regulatory framework, an extreme acceleration of projects will be needed already before 2025.

Figure 14

Cumulative working gas capacity of hydrogen storage projects and storage needs in Europe

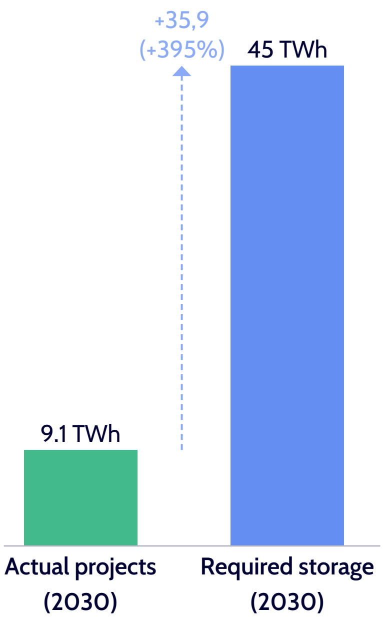


From all the projects across Europe to be built by 2030, Germany is the country where the largest volumes of storage are being developed. The next biggest project announcement for hydrogen storage in Europe are Austria, the UK, France and Spain.

34 To be published by Gas Infrastructure Europe (2023).

Figure 15

Actual project developments and required UHS storage volume in 2030



4.2 Hydrogen storage projects towards 2040 and beyond

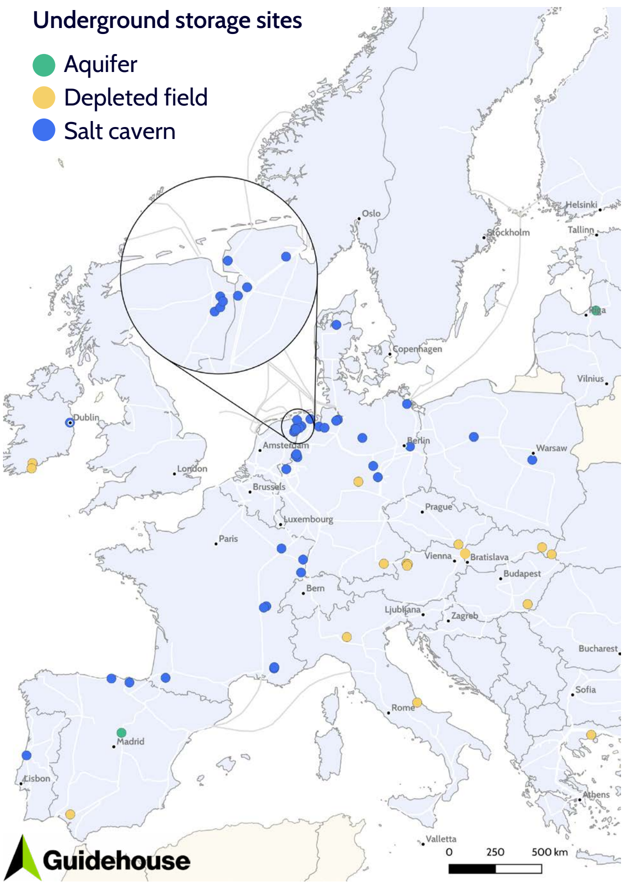
Between 2030 and 2040, the Hydrogen Infrastructure Map indicates around 10 pure-hydrogen storage projects, of which some are more advanced and expected to become utilised to store hydrogen in the early 2030s. This totals 22.1 TWh of pure-hydrogen storage UHS projects.

However, in 2040, the storage requirements have increased massively, based on the uptake of RES deployment across Europe, as well as the increased demand for hydrogen and need for a base supply to various industries. The uncertainty and resulting lack of UHS storage projects after 2040 results in an even larger storage gap than in 2030 for both 2040 and 2050, but it is currently unclear how large that gap will exactly be. In Figure 16, a map of all UHS projects is shown, covering both blended, as well as pure hydrogen storage projects.

The increased gap in 2040 is highly undesirable, as it will result in larger curtailment of RES, higher prices of hydrogen and therefore higher societal costs. There is a large uncertainty in regulation and there is a lack of visibility on a viable business case for UHS that hinder the development of more hydrogen storage projects. These points will need to be addressed to further accelerate the rollout of UHS assets, both towards 2040, as well as towards 2050, when the rollout of RES is even more enormous.

Figure 16

Map of UHS storage projects in 2040[35]



35 Hydrogen Infrastructure Map (2023). Hydrogen storage sites (Last updated in Q4 – 2023)

4.3 Narrowing the gap of underground hydrogen storage as early as 2030

Large infrastructure developments such as UHS require substantial investments upfront. For UHS, this will depend on the type of storage, (pre-)feasi-bility studies, including a geological assessment. This is slightly different for the repurposing of exi-sting natural gas underground storage assets, but still sizeable. More details on the status of techno-logy can be found in chapter 3.

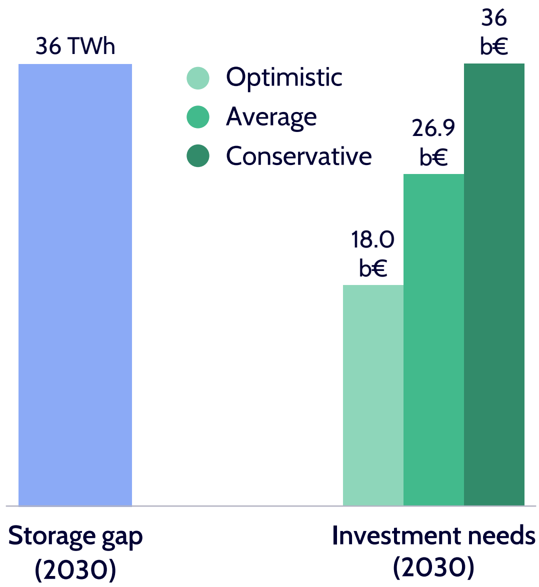
Considering the large storage gap as explained in chapter 4.1 and 4.2, this indicates that significant investments will be required on top of the current project developments. In Table 1 below, the assumed indicative investments per MWh for various technologies is shown, based on optimistic and conservative estimates.

Table 1
Required investments per underground hydrogen storage technology

Technology	Optimistic CAPEX (€/MWh)	Conservative CAPEX (€/MWh)
Salt caverns	700	1100
Hard rock caverns	1000	1400
Depleted gas fields	350	550
Aquifers	350	700

In practice, the actual required investments will depend on local needs, as well available techno-logy, and repurposing possibilities. To give an indication of the size of this investment that relates to this gap, an optimistic, average, and conservative case have been used, corresponding to 500, 750 and 1000 €/MWh. This results in the investment needs of between 18 and 36 billion euros in 2030, as indicated in Figure 17. After 2030, the storage gap with further grow with increasing storage/flexibility needs, which will also result in an incre-asing investment gap.

Figure 17
Underground hydrogen storage gap (left) and related investment needs (right)



As UHS benefits the energy system and the broader stakeholders in society, visibility on the regulatory framework and public support are key to provide certainty to develop these assets. UHS will therefore require public subsidy, either directly or indirectly. Without public support for hydrogen, there is no business case to support the wide deployment of the hydrogen economy, including the storage thereof. The case for the expansion of UHS facilities, especially those needed to support the production of renewable hydrogen, will require CAPEX and/or OPEX subsidies. Subject to compliance with state aid rules and EU funds' rules, the design of support schemes – including what is subsidised, how, and to what extent – is typically left to Member States' discretion under EU law, which will likely also be the case for UHS.

Most EU funds (i.e. Innovation fund, the Connecting Europe Facility, the Horizon Europe instruments, the Just Transition Fund, the Structural Funds, the Recovery and Resilience Facility) can, in principle already fund UHS project, subject to individual projects meeting the specific criteria and being selected among other competing projects. The critical issues in received funds will thus relate to the selection criteria as organised by the EC or other EU bodies.

EU-level regulation affecting national public funding – i.e., mainly the state aid framework – has recently been reformed with the adoption of the new Climate, Energy and Environmental State Aid Guidelines (CEEAGs). These CEEAGs establish a flexible framework to assess national aid towards hydrogen storage projects, under the category of 'aid to infrastructure', which foresees that national aid measures would be assessed almost on a case-by-case basis and without imposing too many strict approval conditions. This flexible category is the one most likely to be applicable to UHS projects, which means that national support to them will be subject to fewer hurdles to obtain the Commission's approval. However, the storage of natural gas and hydrogen blends is not treated as favourably as the storage of pure hydrogen, since it is more likely to fall under another category – applicable to 'aid to decarbonisation' – that is slightly less flexible. In this respect, it will be important that the Commission interpret its own guidelines as much as possible in line with the principle of non-discrimination.

The EU taxonomy recognises the storage of hydrogen as a sustainable activity in principle, subject to meeting certain criteria. The current draft of the screening criteria excludes the storage of hydrogen in storage sites that rely on blending of hydrogen and natural gas. Moreover, the criterion applicable to the operation of the storage facility requires the operator to know that the hydrogen storage qualifies as sustainable hydrogen, which will require a lot of management and contractual setup.

This means, that in principle, there is the possibility to utilise EU and national funds to support closing the investment gap. However, several hurdles are still in place to make this happen. This is clearly visible in the recently published list of Projects of Common Interest (PCI).[36] In this list, only 20 UHS projects were submitted, of which only 7 were selected. Therefore, it will be required to facilitate storage developers to get more mature and suitable projects for future PCI lists, which will help to get (financial) support and scale up. More details on the policy needs and recommendations regarding UHS is given in chapter 5.

4.4 Commitment to flagship projects by H2eart for Europe members

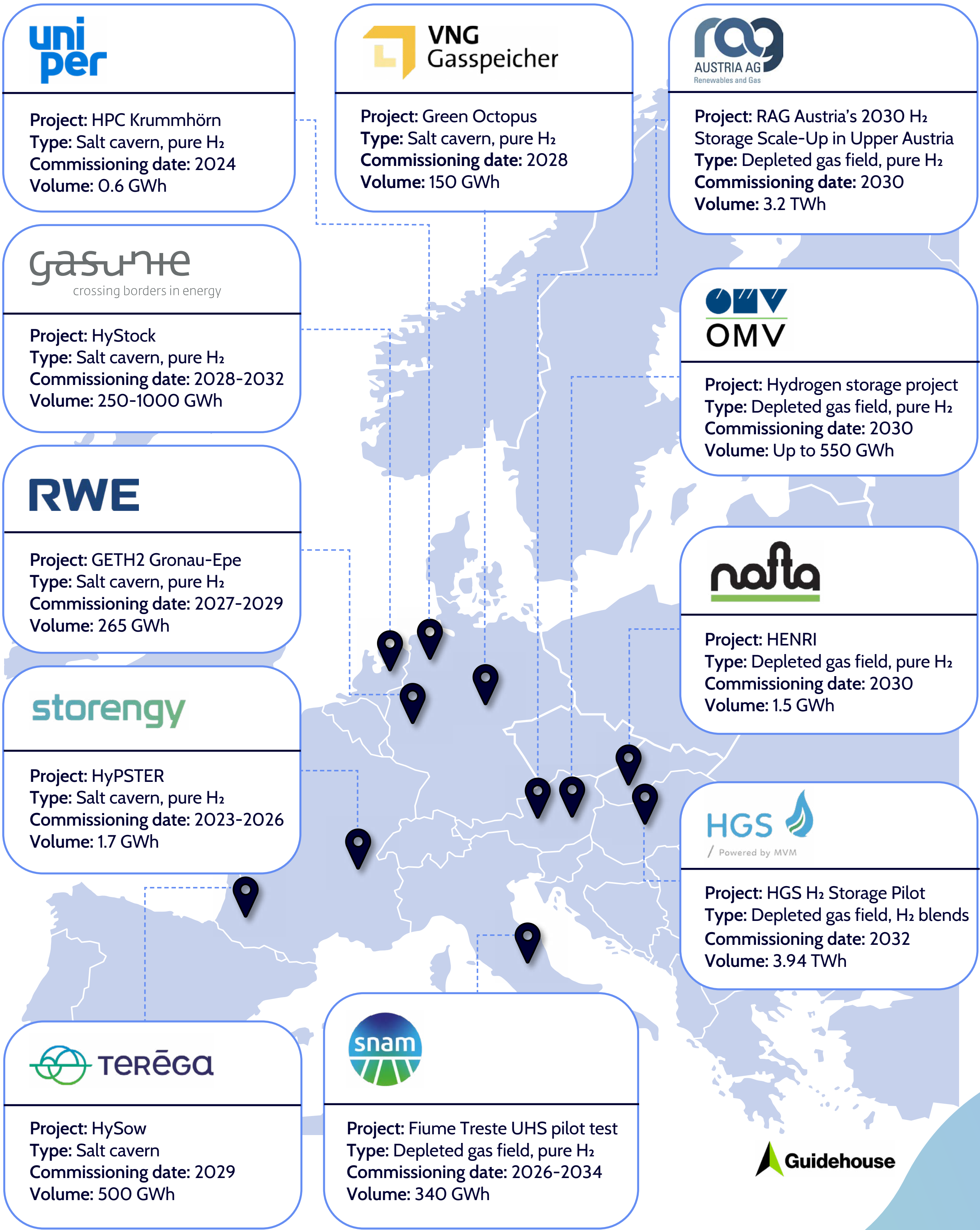
In this alliance, all members are actively working towards the development of UHS across Europe. This is visible in the following projects, that show the ambition to contribute to the further decarbonisation of the European energy system. In Figure 18, a list of flagship projects for all founding members has been included. Note that some of these companies are developing several projects, sometimes in multiple countries.

Currently, the public support for these, and the UHS projects is rather limited, as they are working on pilots, demonstration projects and already on scaling up the storage volumes. However, the companies have the clear ambition to meet the storage requirements as described earlier in this chapter. They all have the goal to accelerate these developments and contribute to a net-zero energy system, both as a group, as well as individual companies in a national context.

36 European Commission (2023) Commission proposes 166 cross-border energy projects for EU support to help deliver the European Green Deal

Figure 18

Flagship projects of the founding members of the H2eart alliance



05
Conclusion and policy overview

Key takeaways

UHS at scale will significantly contribute to the stability & decarbonisation of future energy systems by creating a stable supply of hydrogen for end users and enabling a flexible back-up power production via PtGtP to variably produced renewables.

European hydrogen and RES targets are significant, and their achievement critically hinges on relevant supporting infrastructure, and related targeted policymaking. The European Hydrogen Backbone is already well underway, showing the critical impact of policymaking. Similarly, UHS needs significant efforts from policymakers and key actors from the hydrogen value chain to unlock UHS' full potential and to implement UHS at scale. **Developing a dedicated EU UHS strategy would be key.**

A clear and stable regulatory framework will be required as soon as possible to enable the scale-up of UHS. Delays due to long permitting processes must be minimised to ensure the swift development of the hydrogen storage business case. Stable investment conditions, remuneration models, incentives to develop assets and de-risking measures are essential.

The large gap between actually planned projects and required storage capacity by 2030 and 2040 highlights the need for a hydrogen storage volumes target. A storage target would stimulate actors across the value chain to action, recognise UHS as a key technology for the future energy system and show commitment from EU policymakers.

Successfully decarbonising European energy systems is one of the most pressing challenges of our time. Policymakers and other energy system stakeholders must cooperate to assure a successful and rapid energy transition to allow the achievement of net-zero goals. This report explores how UHS has a key role to play in creating decarbonised and future-proof energy systems and aims to explore all facets of its multiple benefits.

Deploying UHS at scale comes with significant benefits for the hydrogen and electricity ecosystem, and also positively impacts other stakeholders from across the value chain, such as project developers and industries. For example, UHS will help provide a stable supply of hydrogen to end users and enable back-up flexible power production via PtGtP, as well as increase European energy security.

Innovative industry efforts and ambitious investment decisions indicate that industry actors are aware of the vital need for UHS, but also that imminent action is required to deliver a sustainable, resilient, and cost-efficient energy system by e.g. developing large-scale storge close to centres of hydrogen consumption across Europe. Various actions are required to make a more general scale-up reality.

First and foremost, a clear EU-level regulatory framework must be developed urgently as it would significantly contribute to the creation of stable investment conditions. This European framework must be translated into national regulation swiftly to enable local investment in UHS assets. Remuneration models, incentives and de-risking measures to develop assets, as well as financial support for UHS through EU and national financial support mechanisms, such as the IPCEI and the EU fund, shall be required. The regulatory framework should also enable the swift development of a hydrogen storage business and market models where benefits related to security of supply and value of hydrogen storage assets are recognised and properly monetised to create a viable business case.

While different studies report varying storage requirements for 2030 and beyond, the trajectory for UHS projects still shows a significant gap of 36 TWh in 2030, which will increase further towards 2040 and 2050. This was examined in detail in chapter 4. While there are already targets for the deployment of RES, and the utilisation of hydrogen in various industries, the role of large-scale hydrogen storage is not yet acknowledged in clear targets, nor in a trajectory. Setting such a target in future regulations is necessary as it will emphasise the role of UHS as a key technology for the future energy system, will show commitment from the European policymakers to meet decarbonisation targets.

Moreover, lead times of UHS asset development are currently up to 10 years. These delays increase the risk that storage requirements in the future will not be met, resulting in lower decarbonisation across the energy system, and must be significantly shortened. As permitting procedures take up a significant part of the development timeline, it needs to be ensured that national administrative barriers to projects are as low as possible. The Renewable Energy Directive provides many compulsory administrative simplifications for RES which might be extended to UHS projects. Similarly, under the TEN-E regulation, administrative simplifications (one-stop shop, maximum duration, etc.) are provided for Projects of Common Interest (PCI). These previsions must be replicated, at least to some extent, to build capacity and to speed up the deployment of UHS. Shorter development timelines will also result in lower cost and commercial risks associated with UHS deployment, a vital signal to operators to take investment decisions and develop assets.

Integrating UHS within a broader energy system comes with clear benefits. **Nevertheless, to qualitatively and quantitatively assess these benefits, cross-sectoral modelling and energy system planning is needed.** ENTSO-E is currently planning to have an interlinked model available by 2028. However, an interlinked model of electricity, gas and hydrogen with adequate temporal and spatial resolution must be developed as soon as possible to properly assess the benefits of assets and to properly plan the future energy system.

More analysis is needed on where UHS needs are located, what specific technological solutions are best suited for varying end-uses, and on how repurposing can be instrumentalised most efficiently. This analysis should result in a dedicated European Hydrogen Storage Strategy which provides players in the hydrogen ecosystem clarity and builds on the analysis and numbers provided in this report as a starting point.

The role of underground hydrogen storage in Europe

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